RESULTS AND METHODOLOGY OF THE ENGINEERING ANALYSIS FOR RESIDENTIAL WATER HEATER EFFICIENCY STANDARDS

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OVERVIEW

The Energy Policy and Conservation Act, as amended, provides energy conservation standards for water heaters among other products and authorizes the Secretary of Energy to prescribe amended or new energy standards for each type of covered product. This is a preliminary Engineering Analysis; it is part of the analyses the Department will conduct for the water heater rulemaking. The preliminary life-cycle cost analysis will be provided later this month.

The objective of the Engineering Analysis is to determine the costs of increased energy efficiency for residential water heaters by developing price and efficiency data for design options and combinations of design options for each product class. This information will be used in subsequent components of the standards rulemaking process.

The Engineering Analysis uses computer simulation models and other analytical methods to investigate the efficiency improvements of design options and interactions when multiple design options are used. The Engineering Analysis is based on the U.S. Department of Energy's (DOE's) test procedure for residential water heaters.

Manufacturer, distributor, and installer markups, as well as sales tax, are applied to factory costs to arrive at the purchase price of the water heater. Additional installation costs required for certain design options are also included in the consumer price for these design options.

The results of the Engineering Analysis are summarized in cost-efficiency tables demonstrating the increased cost and efficiency due to each design option within each product class. The design options are ranked by cumulative payback period. The energy prices used for this ranking are the current national average energy prices from the Energy Information Administration's (EIA's) Annual Energy Outlook 1998 (AEO98) [1] .

REQUEST FOR STAKEHOLDER COMMENTS

The Department specifically requests comments from stakeholders and other interested parties regarding the following items:

- electric water heaters
  - incremental manufacturing cost for "Insulated Tank Bottom" design option
  - incremental manufacturing cost for "Plastic Tank" design option
  - manufacturer cost-to-retail price markup value

- should fixed costs for 2.5 in. insulation scale with material cost?

• gas-fired water heaters
  - manufacturer cost-to-retail price markup value
  - incremental manufacturing cost for “Side-Arm Heater” design option
  - issues regarding the use of a metal or plastic tank for “Side-Arm Heater” designs
  - maintenance costs for “Side-Arm Heater” designs, due to fouling of the heat exchanger
  - 10-year life for mechanical flue dampers in residential applications
  - should fixed costs for 2.5 in. insulation scale with material cost?
• oil-fired water heaters
  - extended characterization of the baseline model characteristics
  - manufacturer cost-to-retail price markup value.

LIST OF ACRONYMS

AGA	American Gas Association
ADL	Arthur D. Little, Inc.
AEO98	Energy Information Administration's Annual Energy Outlook
ANOPR	Advance Notice of Proposed Rulemaking
ANSI	American National Standards Institute
ARI	Air-Conditioning and Refrigeration Institute
Btu	British thermal unit
CPI	Consumer Price Index
CPSC	Consumer Product Safety Commission
DOE	U.S. Department of Energy
EF	energy factor (from DOE's water heater test procedure)
EIA	Energy Information Administration
EPACT	Energy Policy Act of 1992
EPCA	Energy Policy Conservation Act
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FR	Federal Register
GAMA	Gas Appliance Manufacturers' Association
GRI	Gas Research Institute
GRIM	Government Regulatory Impact Model
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HSI	hot surface ignition
IRR	Internal Rate of Return
LBNL	Lawrence Berkeley National Laboratory
LCC	life-cycle cost
LPG	liquefied petroleum gas
MMBtu	million Btu
MCF	thousand cubic feet
NAECA	National Appliance Energy Conservation Act
NES	National Energy Savings
NFGC	National Fuel Gas Code
NIST	National Institute of Standards and Technology
NOAA	National Oceanic & Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
PVC	polyvinylchloride
RE	recovery efficiency (of a water heater)
RECS	Residential Energy Consumption Survey
SCF	standard cubic foot
SG&A Cost	Selling, General & Administration Cost
TAG	Technical Advisory Group
TSD	Technical Support Document
UA	Standby Heat Loss Coefficient
UEC	unit energy consumption
USC	United States Code
WHAM	Water Heater Analysis Model

INTRODUCTION

The Energy Policy and Conservation Act, as amended, provides energy conservation standards for water heaters among other products and authorizes the Secretary of Energy to prescribe amended or new energy standards for each type of covered product. This is a preliminary Engineering Analysis; it is part of the analyses the Department will conduct for the water heater rulemaking. The preliminary life-cycle cost analysis will be provided later this month.

The objective of the Engineering Analysis is to determine the costs of increased energy efficiency for residential water heaters by developing price and efficiency data for design options and combinations of design options for each product class. This information will be used in subsequent components of the standards rulemaking process. The results of the Engineering Analysis are summarized in cost-efficiency tables demonstrating the increased cost and efficiency due to each design option within each product class. Appendices A through D that are referenced in this report will be available at a later date.

This report describes the analysis of cost and efficiency impacts of specific design options and combinations of design options. Design options used in this analysis are the results of a technology assessment and screening analysis, and comments from stakeholders.

The Engineering Analysis uses computer simulation models and other analytical methods to investigate the efficiency improvements of design options and interactions when multiple design options are used. The Engineering Analysis is based on the U.S. DOE Test Procedure for residential water heaters with a daily draw of 64.3 gallons (243.4 liters), a setpoint of 135°F (57.2°C), an inlet water temperature of 58°F (14.4°C), and an ambient air temperature of 67.5°F (19.7°C) [2].

Manufacturer, distributor and installer markups are applied to factory costs as is sales tax to arrive at the purchase price of the water heater. A fixed markup is derived from retail price data for existing baseline water heater models and applied to manufacturer costs in order to determine consumer prices of design options. Additional installation and costs required for certain design options are also included in the final price for these design options.

Energy prices are the current national average energy prices from the Energy Information Administration’s Annual Energy Outlook 1998 (AEO98) [3] .

INFORMATION SOURCES

The primary source of both manufacturer cost and efficiency data for this analysis was the Gas Appliance Manufacturers’ Association (GAMA). GAMA collected cost and efficiency data from water heater manufacturers. The data was aggregated to protect the confidentiality of the individual manufacturers. GAMA did not provide data for three of the design options being considered (2.5 in. of insulation, plastic tank & side-arm heater). The missing data was supplemented by cost and efficiency information obtained from Max E. Minniear, former Vice President of Engineering at A. O. Smith Water Products Company. Mr. Minniear was contracted by Lawrence Berkeley National Laboratory (LBNL) to provide disaggregated cost and efficiency data for baseline designs and various design options. Some of the cost data was also compared with data obtained from Eugene West, formerly of Bradford-White Corporation, who was under contract with Pacific Northwest National Laboratory (PNNL). Mr. Minniear and Mr. West were both recommended by the Gas Appliance Manufacturers Association (GAMA).

Although computer simulation models were used to generate the efficiency gains expected from design options, GAMA and Mr. Minniear's efficiency estimates were used to confirm the reasonableness of the models' estimates. Other sources of information were used as well. One key source of efficiency data was the GAMA directory [4]. The directory lists energy factor (EF), recovery efficiency (RE), rated input, and first hour rating for residential water heating equipment. The Department accepts listing in the GAMA directory as certification that a model meets the minimum allowable efficiency. Manufacturers' product literature was also collected. It provided additional information about certain design features (e.g., heat traps and thickness of foam insulation). Product literature data were mapped to listings in the GAMA directory to determine what efficiency improvements were employed to reach particular efficiency levels.

Independent confirmation of manufacturer cost data was conducted for certain design options by contacting component manufacturers. In particular, this was done for heat traps and foam insulation. An upper limit to the factory cost of baseline model water heaters was extracted from census data[5]. Factory cost is the manufacturer's cost to make water heaters and includes material, labor, and overhead. The Census Bureau Survey of Manufacturers, Major Household Appliances (MA36F), 1995, reports total value of gas-fired and electric water heaters as $920 million for 8.07 million units sold. This gives an average price per unit of $114. Since this data includes premium models and the manufacturer's markups, as well as warranty costs, freight, profits and commissions, it will be higher than the baseline model factory cost, but it provides an upper limit.

The cost to the consumer for the water heater equipment and the installation cost was established by contacting various plumbing contractors and large retail chains (e.g., The Home Depot, Lowe's, Ferguson, Orchard) throughout the United States.

Other reports, such as the Gas Research Institute (GRI) report, *Assessment of Technology for Improving the Efficiency of Residential Gas Water Heaters*[6] and the Arthur D. Little report, *Market Disposition of High-Efficiency Water Heating Equipment*[7], were used to confirm the reasonableness of the cost, price, and efficiency data. The above GRI report was specifically used to establish the installation cost of gas-fired water heaters requiring an electrical hookup and to estimate the maintenance cost associated with electromechanical flue dampers.

BASELINE MODELS

The determination of product classes and selection of baseline units for the analysis is based on existing DOE water heater efficiency standards[8] and stakeholder comments. The baseline unit represents the most common size water heater with an efficiency equal to the minimum allowed by the existing energy efficiency standards. The general characteristics of each baseline model for each of the three primary product classes (i.e., electric storage, gas-fired storage, and oil-fired storage) are provided below. An in-depth description of each of the baseline models is provided later in this report.

Electric Storage Water Heaters

The baseline model is a 50 gallon (190 liter) glass-lined steel tank with 1½ in. (3.8 cm) of polyurethane foam. The heater has two elements, each with an input of 4500 W. The elements are interlocked so that only one can be energized at a time. The baseline energy factor is 0.86, the National Appliance Energy Conservation Act (NAECA) minimum for this size and type of water heater.

Gas-Fired Storage Water Heaters

The baseline model of gas-fired storage water heaters is a bottom-fired, 40 gallon (150 liter), glass-lined steel tank with a 4-in. (10 cm) center flue. The input rate is 40,000 Btu/hr (11,700 W), with a pilot rated at 400 Btu/hr (120 W). The tank is insulated with 1 in. (2.5 cm) of polyurethane foam. The heater has the minimum efficiency allowed by NAECA with an energy factor of 0.54[9]. It has a recovery efficiency of 76%.

Oil-Fired Storage Water Heaters

The baseline oil-fired water heater is a center-flue design. It has a rated volume of 32 gallons (120 liters), and is insulated with 1 in. (2.5 cm) of polyurethane foam insulation. The input rate is 0.65 gallons per hour (2.5 liters/hr) of oil or 90,000 Btu/hr (26,000 W). It has an EF of 0.53, the minimum allowed by NAECA. The first hour rating is 105 gallons (398 liters), and the RE is 75%. The tank is a cylinder 18 in. (46 cm) in diameter and 32.7 in. (83.1 cm) high, pierced by a 6 in. diameter (15 cm) flue along the central axis. The burner motor, which powers both the blower and oil pump, is rated at **c** hp (282 W). No auxiliary power is consumed during standby. The ignition system on the baseline model is assumed to be the intermittent type and uses a conventional magnetic transformer to achieve the high voltage spark.

SCREENING ANALYSIS OF THE DESIGN OPTIONS

The first step in the rulemaking process is the screening of design options. The purpose of screening is to identify those design options that the Department will consider for the engineering analysis. The screening analysis also provides a discussion of the criteria for eliminating certain design options from further consideration. On July 15, 1996, the Department issued the Process Improvement (Interpretive) Rule (61 FR 36974, July 15, 1996) which establishes the factors DOE uses for screening design options. The factors are as follows:

- Technological feasibility.
- Practicability to manufacture, install and service.
- Adverse impacts on product utility or product availability.
- Adverse impacts on health and/or safety.

In accordance with the Process Improvement Rule, the Department published the results of a preliminary screening of the water heater design options in "**Technology Assessment and Screening Analysis, Appendix B Supplement to the Water Heater Rulemaking Framework", January 1998.** Stakeholders were notified of the availability of this document in the Federal Register on January 14, 1998 (63 FR 2186). The Notice further requested comments on the **Technology Assessment and Screening Analysis** document.

Comment Summary: DOE received 28 comments on the **Technology Assessment and Screening Analysis** document. Six stakeholders including GAMA supported, with modifications, the Department's position regarding the screened design options. The comments addressed air atomized oil burners, power vents and tank bottom insulation for gas or oil-fired water heaters. The majority of comments dealt with the Department's decision to eliminate the heat pump water heater design option from consideration. Those comments from the American Gas Association (AGA) and some gas utilities claimed that DOE must consider all technologically feasible design options to comply with the law (42 U.S.C. Section 6295).

Changes to the Screened Design Options: The baseline electric unit for the present analysis has been assumed to have 1.5 in. of jacket insulation (rather than the 1.0 in. assumed for gas- and oil-fired water heaters) in order to achieve the baseline EF levels. *Increased jacket insulation* levels will be considered in the engineering analysis based on these baseline assumptions. *Heat traps* could be either of plastic or metallic design. Manufacturing costs appear to be roughly comparable between the two, but plastic heat traps are considerably more effective in reducing the water heater standby losses. Therefore, the present engineering analysis will only consider plastic heat traps as a design option. *Air Atomized Burners* were included in the set of design options DOE proposed for consideration in the rulemaking for oil-fired water heaters. However, based on stakeholder comments, the Department has decided not to consider air atomized burners further because they aren't practical to manufacture. A prototype of the air atomized burner has been developed for oil-fired furnaces but the design has not yet been applied to water heaters and the work is being closely followed by the oil-fired water heater industry.

A power vent design was included as part of the discussion of the *Improved Flue Baffle* design option. However, DOE will not consider the power vent design because it requires special venting systems that may not be practical in all situations. Although the American Council for an Energy Efficient Economy claims that this design can go above the 80% RE limit without requiring corrosion resistant flues, the Department believes that any designs above 80 % RE could result in corrosion inside the water heater in colder climates.

Increased Heat Exchanger Surface Area was included in the set of design options the Department proposed to consider. Manufacturers stated that the same efficiency improvement can be achieved by *Improved Flue Baffles* and that this is the preferred approach for residential water heaters.

Additionally, *Increased Heat Exchanger Surface Area* in the form of finned flue surfaces, is being considered as a design option for oil-fired water heaters. Because oil-fired units have a higher input capacity, they can benefit from both improved flue baffles and increased heat exchanger surface areas.

Electric utilities requested that the Department consider the *Tank Bottom Insulation* option for gas or oil-fired water heaters as well. However, DOE has decided not to consider it for safety reasons. The tank bottom is the burner enclosure for gas or oil-fired water heaters, and the high temperatures would pose a safety hazard due to melting insulation.

The gas utility industry would like DOE to consider the *Heat Pump Water Heater* design option. However, the gas utility industry didn't provide any new information to cause DOE to reconsider its earlier decision. The Interpretive Rule addresses how those design options, that are not practicable to manufacture, install and service, should be eliminated from consideration in the engineering analysis. In particular, there are three different sections of the Rule that urge the Department to: (III)(1)(d) "eliminate problematic design options early in the process;" (j) "reduce time and cost of developing standards;" and (III)(11) "be sensitive to first cost increases...avoiding negative impacts to identifiable population groups." Further, the design is not to have adverse impacts on product utility. Providing an equivalent capacity unit (equal to the base case capacity for the electric water heater design) would increase the first cost of the electric water heater significantly. This is also true because heat pumps, in general, are not very efficient at low temperatures $< 50°F$ ($<10°C$) and present designs may not have sufficient capacity to meet normal hot water loads, and hence, may require an electric resistance backup. A Federal Technology Alert[10] issued on the use of residential heat pump water heaters at federal sites shows that they are cost-effective only in select regions of the United States when compared to electric resistance water heating. Since a standard can only cover products which can be practically applied to all situations, the heat pump water heater's adverse impact on consumer utility and lack of adequate servicing infrastructure weighed heavily in the earlier recommendation. Surveys from the Georgia Power and Alabama Power companies reported that over 50 % of their customers would have difficulty installing a heat pump water heater because of space limitations (Arthur D. Little, Inc. 1996[11]). Additionally, many comments to the 1994 Notice of Proposed Rulemaking (59 FR 10464, March 4, 1994) claimed that it was difficult to find people trained to service a heat pump water heater in rural and low-income areas.

AGA argues that DOE relied on “unsubstantiated and uncorroborated” explanations by interested parties in reversing its decision, when in fact, the proposal to keep electric heat pump water heaters as a design option prompted an unprecedented torrent of negative comments following the issuance of the proposed rule in 1994. They are summarized as follows:

- 33 comments questioned the reliability of heat pump water heaters.
- 15 comments cited the space restrictions of small homes, and the increased payback time due to reduced water use.
- 216 comments cited the immature infrastructure for manufacturing, sales and repair, especially in rural areas.
- 66 comments questioned the inconvenience and possible price hikes for larger tank size due to the lower recovery rate, 40 % slower than conventional electric water heaters.
- 21 comments believed it would distort the marketplace and lessen competition among fuel sources.
- 33 comments expressed concerns about increased noise.
- 107 comments feared increased electric rates due to loss of revenues in rural electric cooperatives.
- 22 comments claimed under-the-counter applications would not be cost effective.

Since the late 1970s, when efforts to develop and commercialize heat pump water heaters began, annual sales have not exceeded 10,000 heat pump water heaters (<0.33% of electric water heater sales, <0.17% of all water heater sales). Sales have declined drastically since the mid-1980s, and recent sales are less than 0.1% of all electric water heaters sold. No mass market distribution, sales, installation and servicing infrastructure exists. There is no precedent in the history of the U.S. major appliance industries to suggest that a complete reversal of this situation, on the scale of several million units per year, in only a few years, and in the absence of consumer demand, is possible. Such a reversal would be required if an energy efficiency standard at the heat pump water heater level for electric water heaters is proposed.

The heat pump water heater being developed by DOE does not overcome all of the consumer utility issues because it is designed with a lower recovery rate for average to low hot water usage households. Finally, the Department is concerned that including the heat pump water heater design option could interfere in the market balance between gas and electric utilities.

Table 1 is a list of design options being considered for the engineering analysis and Table 2 is a list of design options that have been eliminated from further consideration.

Table 1. Design Options Used in the Engineering Analysis

Design Options - Description	**Gas**	**Electric**	**Oil**
Heat Traps	X	X	X
Plastic Tank	X(1)	X	
Increased Jacket Insulation	X	X	X
Insulating the Tank Bottom		X	
Improved Flue Baffle	X		X
Increased Heat Exchanger Surface Area			X
Flue Damper (Electromechanical)	X		
Side-Arm Heater	X		
Electronic (or Interrupted) Ignition	X		X

(1) used in conjunction with the side-arm heater option

Table 2. Design Options Eliminated from Further Consideration

Design Options -- Description	**Criteria for Elimination**
Flue Damper (Buoyancy Operated)	Safety issues and lack of long-term use data
Submerged Combustion	Conflict with health and safety codes
Directly Fired	Conflict with health and safety codes
Condensing Option	Venting application restrictions
Condensing Pulse Combustion	Venting application restrictions

Design Options -- Description	Criteria for Elimination
Power Vents	Venting application restrictions
Advanced Forms of Insulation	Fails the practicability to manufacture criterion
U-Tube Flue	Lack of working prototypes and conflict with safety codes
Thermophotovoltaic and Thermoelectronic Generators	Lack of application to water heaters
Reduced Burner Size (Slow Recovery)	Adverse impact on product utility and venting application restrictions
Heat Pump Water Heater Options	Lack of service and installation infrastructure and product utility concerns
Timer Controlled	Not an efficiency improvement option
System Application Options	System installation feature
Increased Heat Exchanger Surface Area	Not as cost effective as the *Improved Flue Baffle* design option for gas-fired units
Air-Atomized Oil Burner	Not practical to manufacture and lack of application to water heaters
Sediment Removal Features	Not an efficiency improvement option
Two-Phase Thermosyphon (TPTS) Design	Fails the practicability to manufacture

EFFICIENCY CALCULATIONS

The energy performance of the baseline unit is mandated by the NAECA minimum efficiency standards, which have been in effect since 1991[12] (Table 3).

Table 3. NAECA Minimum Efficiency Standards

Product Class	**Minimum Allowable Energy Factor** (as of April 15, 1991)
Gas-fired Water Heater	0.62 - (.0019 x Rated Storage Volume in gallons)
Oil-fired Water Heater	0.59 - (.0019 x Rated Storage Volume in gallons)
Electric Water Heater	0.93 - (.00132 x Rated Storage Volume in gallons)

Note: Rated Storage Volume = the water storage capacity of a water heater, in gallons, as specified by the manufacturer.

The design options for each of the three classes of water heaters were modeled either with computer simulation programs or an energy calculation method. The output from the computer simulations was used to determine the energy efficiency characteristics of the water heater (e.g., the EF, RE, and standby heat loss coefficient (UA)), based upon the DOE test procedure. The simulation models and energy calculation methods that were used are discussed briefly below.

WATSIM Model for Electric Storage Water Heaters

WATSIM is a detailed electric water heating simulation program developed by EPRI[13]. WATSIM contains two simulation algorithms; one for the detailed simulation of water heater tanks and the other for controlling water draw profiles for use with the tank model. Since the simulation analysis must be performed according to the requirements of the DOE test procedure, the water draw profile is specified to the 64.3 gallon (243.4 liter) draw pattern in the test procedure. The output of WATSIM does not include the EF, RE, and UA calculations from the DOE test procedure. However, it does provide detailed temperature profiles of the water inside the tank of the water heater during the simulation run (the temperature profile is provided in a standard WATSIM output file called *tw_vs_t1.out*). These temperature readings are used to determine the EF and other parameters of the water heater using the test procedure calculations. A spreadsheet tool has been developed to calculate the efficiency characteristics per the specifications of the DOE test procedure from the output contained in the *tw_vs_t1.out* file. Appendix A provides a detailed description of the procedure to determine the efficiency characteristics using the WATSIM output.

TANK Model for Gas-Fired Storage Water Heaters

TANK is a detailed gas-fired storage water heater program developed by Battelle for the GRI[14]. TANK calculates energy flows throughout the water heater including heat gained or lost by the water, flue heat losses, jacket heat losses, fittings heat losses, and combustion chamber heat losses. Unlike WATSIM, the outputs of TANK include the EF, RE, and UA from the DOE test procedure. Therefore, calculations outside of TANK are not necessary for determining the gas-fired water heater's energy efficiency characteristics under DOE test procedure.

As will be discussed in more detail later, there are limits to how high the flue-loss efficiency can be increased before changes are required of the vent system to prevent flue gas condensation. Recent discussions with Battelle[15] indicate that TANK may provide inaccurate estimates of the flue-loss efficiency. However, because of insufficient data, DOE has decided, for now, to rely on TANK predictions. Therefore the Engineering Analysis will continue to use TANK's estimates of the flue-loss efficiency to indicate whether modifications to the vent system are necessary.

WHAM Energy Calculation for Oil-Fired Storage Water Heaters

A simplified water heater analysis model (WHAM) was used for the Engineering Analysis for oil-fired water heaters. WHAM is based on the 24 hour simulated use test portion of the DOE test procedure. The model is an equation to calculate energy consumption from the RE, UA, and rated input (P_{on})[16]. The WHAM energy calculations have been checked against both the WATSIM and TANK simulation models to verify that the energy consumption calculations are sufficiently accurate. The WHAM energy calculation is based on an idealized version of a water heater. The water temperature is assumed to remain at the setpoint throughout the tank. Also RE and UA are assumed to be constant. The equation is listed below.

$$Q_{in} = \frac{vol \cdot dens \cdot C_p \cdot (T_{tank} - T_{in})}{RE} \cdot \left[1 - \frac{UA \cdot (T_{tank} - T_{amb})}{P_{on}} \right] + 24 \cdot UA \cdot (T_{tank} - T_{amb})$$

where;

- Q_{in} = average daily energy input,
- RE = recovery efficiency from test procedure,
- UA = standby heat loss coefficient from test procedure,
- P_{on} = rated input,
- vol = average volume of water drawn in 24 hours,
- T_{tank} = tank thermostat set point,
- T_{in} = inlet water temperature,
- T_{amb} = ambient air temperature surrounding the water heater
- $dens$ = density of water, and
- C_p = specific heat of water.

Daily energy use predictions from WHAM for oil-fired water heaters were not directly compared against daily use predictions from any oil-fired water heater simulation model (such as TANK or WATSIM) as no simulation model exists for oil-fired water heaters. However, the results of the WHAM equation have been compared against results of detailed simulation models of residential electric and gas-fired storage water heaters with excellent agreement. A detailed explanation of the WHAM approach is included in Appendix B.

It is believed that WHAM is a good predictor of daily energy use for oil-fired water heaters because one of the simplifying assumptions is that all the water drawn from the tank is at the set point temperature. For a given draw volume (such as the separate 10.7 gallon (40.5 liter) draws of the DOE test), the oil-fired water heater will fire at approximately the same time as would a gas-fired water heater of similar volume. However, since the recovery rate of oil-fired water heaters is typically over twice that of residential gas fired water heaters, the temperature of the water being drawn from the heater will, on average, be closer to the water heater set point temperature.

TECHNOLOGICAL ISSUES

There are impending regulatory changes outside of the NAECA efficiency standards process that will impact the manufacture or installation of water heaters. Some of these changes affect the efficiency of water heaters as well. These issues are described here, along with the methods that were used to address each issue.

Insulation

Most residential water heaters are insulated with polyurethane foam in the space between the tank and the jacket. The insulation is foamed in place using polyols and isocyanates that react to form a polyurethane foam. A blowing agent included in the mixture is vaporized by the heat of reaction creating a frothy mass that hardens quickly into closed-cell foam insulation. Currently, water heater manufacturers use HCFC-141b, an ozone depleting substance, as a blowing agent. As a result of the Montreal Protocol, the U.S. Environmental Protection Agency has scheduled the phase out of this blowing agent by the year 2003[17]. Water heater manufacturers must use another blowing agent after that time.

One of the leading alternatives for use as a blowing agent appears to be HFC-245fa. This blowing agent is being adopted by the refrigerator industry and should be available in sufficient quantity by 2003. At the temperatures found in water heaters, information from Bayer and Battelle reports shows that it does have a slightly higher k-factor than the current blowing agent[18,19]. Based on this information, Table 4 presents conductivity comparisons of foam insulation blown with HCFC-141b and HFC-245fa. The average increase in conductivity resulting from replacing HCFC-141b with HFC-245fa is 3.0%.

Table 4. Conductivity Comparisons between Foam Insulation Blown with HCFC-141b and HFC-245fa

		Conductivity @ 100°F (37.8°C)	
		HCFC-141b	**HFC-245fa**
Source	**Type of Foam Panel**	*Btu-in/hr·ft·°F (W/m·K)*	*Btu-in/hr·ft·°F (W/m·K)*
Bayer	5% pack, 2 in. (5.1 cm) panel	0.149 (0.0214)	0.151 (0.0218)
Bayer	10% pack, 2 in. (5.1 cm) panel	0.148 (0.0212)	0.154 (0.0221)
Bayer	5% pack, 3 in. (7.6 cm) panel	0.152 (0.0220)[a]	0.155 (0.0223)
Bayer	10% pack, 3 in. (7.6 cm) panel	0.150 (0.0217)[a]	0.154 (0.0221)
Bayer	not specified	0.146 (0.0211)	0.154 (0.0221)
Battelle	not specified	0.166 (0.0239)	0.172 (0.0247)
Average Conductivity Increase			**3.0%**

The analysis for the DOE water heater energy efficiency standards is based on the properties of insulation blown with HFC-245fa and the most realistic estimates of costs and physical parameters available for HFC-245fa. In order to keep the efficiency and energy use characteristics of water heaters with HFC-245fa insulation the same as those with HCFC-141b insulation, it was necessary to compensate for the 3.0% higher k-factor. This was accomplished by modeling the water heaters with slightly thicker insulation. In addition to the extra volume and cost of insulation, the amount and cost of steel used for the water heater jacket were also increased.

The industry is also considering other blowing agents in addition to HFC-245fa including HFC-356mffm, HFC-134b, cyclo-pentane, and water blown foams. Water blown foams are created when water is mixed into one of the components and participates in the chemical reaction leading to polyurethane causing the release of CO_2 which provides the blowing activity. Although the above blowing agents are currently being investigated as possible replacements to HCFC-141b by the water heater industry, the analysis presented in this report is based on the use of HFC-245fa.

DOE, in collaboration with the National Institute of Standards and Technology (NIST) and Pacific Northwest National Laboratory, is testing the relative performance of HCFC-141b, HFC-245fa and water-CO_2 foam blowing agents on water heater performance. The approach of the analysis is to measure the thermal conductivity of blocks foamed with each blowing agent in a guarded hot plate test, and perform a DOE 24-hour simulated use test on tanks foamed with each blowing agent. Twelve 50-gallon (190 liter), dual-element electric water heater tanks were provided by Bradford White and shipped to BASF, a foaming supplier for foaming. BASF foamed a set of four samples (consisting of four tanks and four blocks) with each blowing agent. The foaming of tanks with each blowing agent was timed to ensure a similar aging period has passed prior to the time they are tested. The foaming was carried out, to the extent possible, in accordance with standard industry practices. BASF, on the basis of their expertise and experience, and in consultation with industry experts, determined the appropriate parameters regarding the formulation of the resin and blowing agent material. The samples, consisting of foam blocks and tanks were shipped to NIST where the following tests were conducted:

> Guarded Hot Plate: A one meter guarded hot plate operated in two-sided mode was used to measure the thermal conductivity of the insulation blocks. The cold plates were set to 67.5°F (19.7°C). Thermal conductivity measurements were made at hot plate temperatures of 100.0°F (37.8°C), 120.0°F (48.9°C), and 140.0°F (60.0°C).
>
> DOE 24-Hour Test: NIST used the DOE 24-hour simulated use test to determine EF. The EF test was conducted on at least three of the four tanks. An infrared camera was used during the DOE test to inspect for gross voids or bridges in the tank insulation. If the infrared inspections and EF results were consistent between samples of a given blowing agent type, NIST could, at its discretion, eliminate the fourth tank from the testing sequence.

All final results of the tests will be fully documented and provided to the DOE. The test results will be used to verify the assumed thermal conductivities of the foam insulations used in the Engineering Analysis. Subsequent revisions to the Engineering Analysis will update the insulation conductivities as dictated by the test results.

Flammable Vapor Ignition

Current designs for gas-fired water heaters rely on a standing pilot to ignite the main burner. If flammable vapors are in the air near a water heater, there is the possibility of unintended ignition. This is a potential safety problem because water heaters are often installed in garages and basements, where flammable liquids such as gasoline or paint thinners may be used.

The Consumer Product Safety Commission (CPSC) is working with GRI and the water heater industry to develop a test procedure for gas-fired water heater designs that will prevent ignition of flammable vapors[20]. American National Standards Institute (ANSI) is anticipated to adopt a test procedure regarding water heater resistance to igniting flammable vapors in 1999.

From discussions with the Water Heater Industry Joint Research and Development Consortium, DOE will use a placeholder value of $35 as additional cost for designs to prevent ignition of flammable vapors. In this analysis, the extra $35 is applied to the manufacturer cost of all design options for gas-fired water heaters, including the baseline design. Thus, the added cost of preventing flammable vapor ignition does not impact the cost effectiveness of any energy efficiency design improvement. The design is also assumed not to require electricity at the water heater or modifications of the venting system. No changes in efficiency are expected from flammable vapor ignition resistant water heater designs. This situation will be monitored to verify these assumptions or to update the analysis as designs meeting the ANSI standard become available.

Venting

Use of gas-fired water heaters with flue-loss efficiency greater than 80% with existing venting systems that are not designed for low temperature flue gases can potentially lead to excessive corrosion and failure of the vent system[21,22] in certain climates. The Department has recognized this potential problem and decided to incorporate, where necessary, the costs of venting modifications to gas water heater installation costs. In this section, recommendations derived from previous studies conducted by the gas industry are outlined. Appendix C of this report provides more details on the impacts of using high-efficiency water heaters on vent system corrosion and its prevention.

GRI has estimated that 53% of U.S. residences have common vent systems for water heaters and furnaces (Paul 1991). With increased minimum furnace efficiency requirements (since 1992), most replacement furnaces have a higher efficiency than the existing units they are replacing. Although masonry chimneys are quite resilient to corrosion, relining may be necessary when an existing low flue-loss efficiency (<80%) furnace is replaced with a high flue-loss efficiency furnace (>80%). Because furnace on-times are significantly higher than water heater on-times, the furnace usually dries any condensate deposited in the masonry chimney by the water heater. With the use of high flue-loss efficiency furnaces, the flue gas temperatures are lower, increasing chimney wet-times.

Most water heaters sold today are for the replacement market. In almost all replacement situations, there are vent systems and reliners available in the market to meet the venting requirements for installing high flue-loss efficiency water heaters. Hence, there is no technological barrier to use a high flue-loss efficiency water heater in a replacement situation.

Table 5 summarizes the recommendations for a two-appliance configuration. A base case configuration is assumed to have two natural draft appliances (a furnace and a water heater, for example) venting into a common vent system. The flue-loss efficiency of each of these units is assumed to be less than 80%. The vent connectors are assumed to be single wall metallic connectors and the vent is assumed to be an exterior masonry chimney that is properly sized.

Table 6 summarizes the recommendations for a one-appliance configuration. A base case configuration is assumed to have a natural draft water heater venting into an exterior masonry vent system. The flue-loss efficiency of the unit is assumed to be less than 80%. The vent connectors are assumed to be single wall metallic connectors and the vent is assumed to be an exterior masonry chimney that is properly sized. This table shows that design options and combinations of design options, which result in a flue-loss efficiency of 80% or less can be vented into systems that follow the National Fuel Gas Code [23] standards for venting systems with no additional cost.

Table 5. Summary of General Recommendations for Relining Exterior Masonry Chimneys for Residential Installations in a Two-Appliance Configuration

Option	Comment
Base case: both furnace and water heater flue-loss efficiency less than 80%	No relining is necessary
Replace base case water heater with 80.5% efficient (flue-loss) unit	No relining is necessary
Replace base case water heater with 83% efficient (flue-loss) unit	Relining may be needed in most DOE regions
Replace base case furnace with 83% efficient (flue-loss) unit (fan-assisted)	Relining of the chimney is recommended in all regions except DOE region I (Phillips 1994)
Replace base case water heater and furnace with high flue-loss efficient units	If the flue-loss efficiency is between 80.5% and 83%, chimneys in some DOE regions may need relining. If the flue-loss efficiency is above 83%, relining is recommended in all regions except region DOE region I.
“Orphaned” water heater	Relining is recommended in all DOE regions

Table 6. Summary of General Recommendations for Relining Exterior Masonry Chimneys for Residential Installations in a One-Appliance Configuration

Option	Comment
Base case: flue-loss efficiency of the water heater is less than 80%	No relining is necessary
Replace base case water heater with 80.5% efficient (flue-loss) unit	No relining is necessary
Replace base case water heater with 83% efficient (flue-loss) unit	Relining may be needed in most DOE regions, except DOE region I

Another important consideration is the configuration of the vent connector - the portion of the vent system connecting the gas appliance flue collar or draft hood to the vent. A single wall vent connector limits the flue-loss efficiency of gas appliances to 80% in a worst case installation. Therefore, if the flue-loss efficiency of the water-heater or the furnace (two-appliance configuration) exceeds 80% it is recommended that a double wall vent connector be used (Paul et al. 1992, Talbert et al. 1995).

OVERALL ANALYSIS APPROACH

In this report, a distinction has been made between baseline models containing current technologies and future baseline models which are expected to incorporate new mandated features. The former are referred to as “existing” baseline models and the latter as “analytic” baseline models. An important feature of existing water heater technology is the insulation based on HCFC-141b as a blowing agent. Additionally, for the purposes of the analysis, a representative, or “typical” tank size (rated volumes of 50-gal for electric, 40-gal for gas-fired, and 32-gal for oil-fired) has been chosen from all the standard sizes for each fuel type. The first half of this discussion concerning costs and prices will address only the typical existing baseline models.

ELECTRIC WATER HEATERS

The Engineering Analysis models the design options for electric water heaters using WATSIM, a detailed computer simulation model for water heaters developed by EPRI. A 50 gallon (190 liter) rated volume electric resistance water heater is used as the existing baseline model for this analysis.

Existing Typical Baseline Model

In using WATSIM to establish the typical existing baseline model, the goal was to establish the characteristics of a 50 gallon (190 liter) baseline electric water heater which would yield a 0.86 EF (the minimum EF allowed by NAECA for a 50 gallon electric water heater).

GAMA's directory of certified water heaters and product literature from various manufacturers shows three models of 50 gallon (190 liter) electric water heaters with an energy factor of 0.86. Two models accomplished this through the use of heat traps and 1 in. (2.5 cm) of foam insulation (American E51-50H-045D and Bradford White M-I-50T6DS) while one model achieved a 0.86 EF solely through the use of 1 in. (2.5 cm) of foam insulation (Rheem 81V52D). It should be noted that the foam insulation in the above models is blown with HCFC-141b. Since the literature indicated that a 0.86 EF was achievable solely through the use of 1 in. (2.5 cm) of foam insulation, the first typical existing baseline water heater modeled incorporated only this single energy-efficiency design feature. Table 5 summarizes the primary characteristics of the typical existing baseline water heater first simulated with WATSIM.

Table 7. Initial Existing Electric Water Heaters Baseline Characteristics*

Tank Diameter	15.84 in. (40.23 cm)
Tank Length	54.48 in. (138.38 cm)
Insulation Thickness - Sides	1.00 in. (2.54 cm)
Insulation Thickness - Top	1.00 in. (2.54 cm)
Conductivity of Feed-Throughs (equivalent to steel)	0.40 Btu/ft·min·°F (41.54 W/m·K)
Natural Convection UA for Feed-Through calcs (no heat traps)	0.578 Btu/hr·°F (default in WATSIM)

Note: * Units in the table are consistent with the units used by the WATSIM simulation model.

Simulations of a water heater with the baseline characteristics listed in Table 7 yielded a surprisingly low EF of 0.805. WATSIM's simulation results were then compared to those from TANK (GRI's gas-fired water heating simulation model) to determine the cause of its low EF estimate. For comparably sized water heaters, WATSIM's pipe heat loss estimates were approximately twice that of TANK's. Since during TANK's development its performance was validated against actual test data, WATSIM's method for calculating feed-through losses was suspected of being inaccurate. To confirm this, additional simulations were conducted to determine whether any specific water heater characteristics could significantly impact EF, thereby ruling out the high feed-through losses as being the cause of the low EF estimate. But the simulations could not identify any physical parameters, besides the addition of heat traps or an increase in the thickness of the foam insulation, which could reduce water heater losses enough to yield a significantly large impact on EF. Thus, WATSIM's default feed-through losses were concluded to be the likely cause for its low EF estimates. EPRI confirmed that WATSIM's feed-through loss estimates were indeed too high, although no indication was given as to the magnitude of the error[24].

New simulations were conducted after reducing WATSIM's feed-through loss estimates to those predicted by TANK. Lower feed-through losses were realized by lowering the natural convection UA values at the supply and draw lines and by adding 1/8" pipe insulation for modeling purposes only. By using the same initial baseline characteristics as listed previously with the exception of a UA value of 0.185 Btu/hr °F rather than 0.578 Btu/hr °F, for natural convection feed-through losses, a 0.830 EF was predicted. Because the EF estimate was still 0.030 points lower than the target value of 0.860 EF, the thickness of the foam insulation was increased from 1 to 1½ in. (2.5 to 3.8 cm). An 0.858 EF was achieved as a result of making this change. Thus, the typical existing baseline model as simulated by WATSIM was able to achieve the minimum allowable NAECA efficiency of 0.86 EF through the use of 1½ in. (3.8 cm) of foam insulation.

Table 8 describes the physical details of the typical existing baseline model electric water heater used in this analysis. These values describe the water heater in engineering terms for use in the WATSIM simulation model.

Table 8. Electric Water Heater Existing Baseline Model Characteristics*

Descriptive parameter		**Value**
tank:	diameter	15.8 in. (40.1 cm)
	height	54.5 in. (138.4 cm)
	wall thickness	0.063 in. (0.16 cm)
	wall conductivity	0.40 BTU/ft·min·°F (41.5 W/m·K)
	support ring conductivity	0.40 BTU/ft·min·°F (41.5 W/m·K)
height of concave bottom dome		1.5 in. (3.8 cm)
heat transfer coefficient for tank wall film		20.0 BTU/hr·ft^2·°F (113.5 W/m^2·K)
tank insulation - thickness	top:	1.5 in. (3.8 cm)
	side:	1.5 in. (3.8 cm)
	bottom:	0.75 in. (1.91 cm)
tank insulation - conductivity	top:	0.000233 BTU/ft·min·°F (0.0242 W/m·K)
	side:	0.000233 BTU/ft·min·°F (0.0242 W/m·K)
	bottom:	0.000333 BTU/ft·min·°F (0.0346 W/m·K)
cold water inlet height		7.5 in. (19 cm)
hot water outlet height		54.5 in. (138 cm)
heater elements - height	1:	7.44 in. (18.9 cm)
	2:	38.9 in. (98.8 cm)
heater elements - power	1:	4.50 kW
	2:	4.50 kW

heater elements - efficiency	1:	100%
	2:	100%
thermostats - height	1:	12.0 in. (30.5 cm)
	2:	43.7 in. (111 cm)
feed-throughs - height	1:	54.5 in. (138 cm)
	2:	54.5 in. (138 cm)
	3:	1.56 in. (3.96 cm)
	4:	54.5 in. (138 cm)
feed-throughs - conductivity	1:	0.40 BTU/ft·min·°F (41.5 W/m·K)
	2:	0.40 BTU/ft·min·°F (41.5 W/m·K)
	3:	0.0018 BTU/ft·min·°F (0.1869 W/m·K)
	4:	0.40 BTU/ft·min·°F (41.5 W/m·K)
feed-throughs - insulation thickness	1:	0.12 in. (0.30 cm)
	2:	0.12 in. (0.30 cm)
	3:	0
	4:	0
feed-throughs - orientation	1:	vertical
	2:	vertical
	3:	horizontal
	4:	vertical
feed-throughs - radius	1:	0.5 in. (1.3 cm)
	2:	0.5 in. (1.3 cm)
	3:	0.5 in. (1.3 cm)
	4:	0.5 in. (1.3 cm)
feed-throughs - length	1:	24.0 in. (61.0 cm)
	2:	24.0 in. (61.0 cm)
	3:	6.0 in. (15.2 cm)
	4:	3.6 in. (9.1 cm)
feed-throughs - wall thickness	1:	0.036 in. (0.091 cm)
	2:	0.036 in. (0.091 cm)
	3:	0.036 in. (0.091 cm)
	4:	0.036 in. (0.091 cm)
feed-throughs - insulation conductivity	1:	0.000233 BTU/ft·min·°F (0.024196 W/m·K)
	2:	0.000233 BTU/ft·min·°F (0.024196 W/m·K)
	3:	0
	4:	0
feed-throughs - natural convection pipe loss	1:	0.185 BTU/hr·°F
	2:	0.185 BTU/hr·°F
	3:	0.0
	4:	0.0

Note: * Units in the table are consistent with the units used by the WATSIM simulation model.

Modeling Design Options

As listed in Table 1, there are only four design options that are being considered to improve the efficiency of electric storage water heaters. Each design option is briefly discussed below along with how it was modeled with WATSIM. The discussion begins with the analysis of the baseline model using foam insulation blown with HFC-245fa rather than HCFC-141b. As noted before this baseline model is referred to as an “analytic” baseline model.

Analytic Baseline Model. The blowing agent currently utilized by the water heater industry for foam insulation, HCFC-141b, is scheduled to be phased out by 2003. Because new energy-efficiency standards are expected to take effect near the phase out date of HCFC-141b, the baseline model for this analysis must utilize foam insulation blown with an acceptable alternative blowing agent. The most likely alternative to replace HCFC-141b appears to be HFC-245fa. According to published reports, HFC-245fa has a 3.0% higher conductivity than HCFC-141b. Thus, the conductivity value of the foam insulation in the existing baseline model listed in Table 8 was increased by 3.0% to a value of 0.000240 Btu/ft·min·°F (0.0249 W/m·K) (the conductivity increase was also applied to the feed-through insulation). In addition, the thickness of the foam insulation surrounding the tank was increased to 1.55 in. (3.94 cm) to compensate for the increased conductivity of the insulation. This increase in insulation thickness also resulted in an increase of jacket material. Table 9 summarizes the changes that were made to the insulation conductivity of a typical existing baseline model with HCFC-141b in order to simulate its performance with HFC-245fa.

Table 9. Electric Water Heater Modeling Differences: Existing vs. Analytic Baseline Model - Insulation Conductivity*

Descriptive parameter	Baseline w/ HFC-141b	Baseline w/ HFC-245fa
insulation conductivity	0.000233 BTU/ft·min·°F (0.02420 W/m·K)	0.000240 BTU/ft·min·°F (0.024922 W/m·K)

Note: * Units in the table are consistent with the units used by the WATSIM simulation model.

Heat Traps. The heat conducted and convected through the fittings (water pipes, drain valve, pressure relief valve, and thermostat) accounts for a significant portion of the total standby loss in a typical residential-size water heater[25]. A heat trap is a device or arrangement of piping that keeps the buoyant hot water from circulating through a piping distribution system because of natural convection. When there is no draw of hot water, this device prevents water in the hot water outlet line from getting back into the tank as it cools off; and prevents hot water in the tank from circulating back out into the cold water inlet line. Thus, by containing the hot water in the storage tank, the heat trap minimizes standby loss. These devices can be integral to the tank design or independently attached to the inlet and outlet pipes during installation.

Conventional heat traps are currently made in two styles. In the first style, a floating plastic ball blocks the cold water inlet. The buoyancy of the plastic holds it in place until water is drawn. The force of water is strong enough to push the ball out of the way as water enters the tank. The second style is used for the hot water outlet. In this heat trap, the ball is denser than water, and the weight of the ball seals the outlet until hot water is drawn and the water pressure lifts it out of the way. A small bypass channel is left for water to escape back into the inlet line from the tank. This is necessary because after a large draw fills the tank with cold water, the water expands as it is heated. Other heat trap designs have also been invented and produced. These include U-shaped pipes[26], flexible seals[27], flaps, springs, and other mechanisms.

For this analysis, heat traps were analyzed as being either metal or plastic. Both types of heat traps prevent the losses associated with the circulation of hot water into the piping distribution system.

For purposes of this analysis, metal heat traps are considered to be those devices which are attached to the inlet and outlet pipes. Plastic heat traps are considered to be those devices which are integral to the tank design. On the inlet side, the plastic heat trap is part of a plastic dip tube assembly where the heat trap mechanism resides near the top of the water heater but within the tank. On the outlet side, the plastic heat trap is part of a heat trap/anode device where the heat trap mechanism is part of a plastic cartridge enclosed within the steel pipe that houses the entire heat trap/anode device.

To simulate the performance of heat traps, the UA values for calculating the natural convection heat transfer losses at the supply and draw lines were lowered by a magnitude of 0.122 Btu/hr·°F[28]. The above procedure models the heat losses associated with hot water recirculation. TANK, the simulation tool for the modeling of gas-fired storage heaters, models both metal and plastic heat traps. Based upon modeling the performance of a 40 gallon (150 liter) gas-fired water heater with TANK, plastic heat traps prevent losses of approximately 500 Btu/day (530 kJ/day) relative to metal heat traps. To model plastic heat traps in WATSIM, the conductivity of the insulation surrounding the supply and draw lines was decreased to achieve the 500 Btu/day (530 kJ/day) savings. Table 10 summarizes the changes made to the analytic baseline model (with HFC-245fa) in order to simulate the performance of metal and plastic heat traps.

Table 10. Electric Water Heater Modeling Differences: Analytic Baseline Model vs. Models with Metal and Plastic Heat Traps*

Descriptive parameter		Analytic Baseline	with Metal Heat Traps	with Plastic Heat Traps
feed-throughs - insulation	1:	0.000240 BTU/ft·min·°F (0.024922 W/m·K)	0.000240 BTU/ft·min·°F (0.024922 W/m·K)	0.000010 BTU/ft·min·°F (0.001308 W/m·K)
conductivity	2:	0.000240 BTU/ft·min·°F (0.024922 W/m·K)	0.000240 BTU/ft·min·°F (0.024922 W/m·K)	0.000010 BTU/ft·min·°F (0.001308 W/m·K)
feed-throughs - natural convection	1:	0.185 BTU/h·°F	0.063 BTU/h·°F	0.063 BTU/h·°F
pipe loss	2:	0.185 BTU/h·°F	0.063 BTU/h·°F	0.063 BTU/h·°F

Note: * Units in the table are consistent with the units used by the WATSIM simulation model.

Increased Jacket Insulation. The jacket (sides and top) of the water heater is insulated with polyurethane foam or fiberglass. Because polyurethane foam has a lower thermal conductivity than fiberglass and is cheaper to install in large volume manufacturing, it is used almost exclusively. Most water heaters on the market today have at least 1-in. (2.5 cm) thick foam insulation, while some manufacturers provide 2- or 3-in. (5.1 or 7.6 cm) thick insulation, as well. Although increasing the insulation thickness reduces the standby loss, the increase in the overall diameter of the water heater may pose some installation problems. There will also be an increase in shipping costs because fewer heaters will fit in a truck. Because of these potential installation problems, maximum insulation thicknesses were limited to 2½ in. (6.4 cm) for this analysis.

Table 11 summarizes the changes made to the analytic baseline model (with HFC-245fa) to simulate the performance of an electric water heater insulated with 2- and 2½-in. (5.1 cm and 6.4 cm) of foam insulation.

Table 11. Electric Water Heater Modeling Differences: Analytic Baseline Model vs. Models w/ 2 & 2½ in. of foam insulation

Descriptive parameter		Analytic Baseline	with 2 in. of foam insulation	with 2½ in. of foam insulation
tank insulation - thickness	top:	1.55 in. (3.94 cm)	2.00 in. (5.08 cm)	2.50 in. (6.35 cm)
	side:	1.55 in. (3.94 cm)	2.00 in. (5.08 cm)	2.50 in. (6.35 cm)

Insulating the Tank Bottom. The bottom of the tank of an electric water heater can be insulated with polyurethane foam to reduce the standby heat losses. The use of polyurethane foam insulation underneath the tank bottom is not conventional practice. Currently, manufacturers might place fiberglass insulation in the space allotted underneath the bottom of the water heater due to the concaveness of the tank. For this analysis, the height of the baseline model's concave dome is assumed to be 1½ in. (3.8 cm) with ¾ in. (1.9 cm) of fiberglass insulation stuffed below it.

In modeling foam insulation for the tank bottom it was assumed that a foamed "disk/bottom insulation" assembly would be used. WATSIM models the heat transfer through the bottom of the tank by two separate parallel heat transfer paths - "bottom" and "support ring". The "bottom" represents the area of the concave dome and the "support ring" represents the perimeter, which is a continuation of the tank wall below the bottom of the tank. The "bottom insulation" portion of this assembly fills the domed space underneath the tank. The "disk" portion is assumed to lie underneath both the support ring and the "bottom insulation". Although the "disk" portion of this assembly is assumed to be only c in. (3.2 mm) thick, water heater construction practices prevent the support ring from deforming it, when the tank is filled with water. The adhesive and structural properties of the foam insulation keep the tank from crushing the bottom insulation. The bottom insulation portion of the "disk/bottom insulation" assembly reduces the heat losses from the bottom of the tank, while the disk portion reduces the conduction heat losses through the support ring.

Table 12 summarizes the changes made to the analytic baseline model to simulate the performance of electric water heaters with bottom insulation. The support ring conductivity is assumed to be 50% steel and 50% foam insulation. As a result, its conductivity was twice that of foam insulation.

Table 12. Electric Water Heater Modeling Differences: Analytic Baseline Model vs. Model with Foamed Bottom Insulation*

Descriptive parameter	Analytic Baseline	Foamed Bottom Insulation
tank:support ring conductivity	0.40 BTU/ft·min·°F (41.54 W/m·K)	0.000472 BTU/ft·min·°F (0.0490 W/m·K)
tank insulation - thickness bottom:	0.75 in. (1.91 cm)	1.5 in. (3.8 cm)
tank insulation - conduct.bottom:	0.000333 BTU/ft·min·°F (0.0346 W/m·K)	0.000240 BTU/ft·min·°F (0.0249 W/m·K)

*Units in the table are consistent with use by WATSIM.

Plastic Tank. There are at least two methods for constructing plastic water heater tanks. One method uses a seamless, blow-molded polybutylene inner tank with a filament-wound fiberglass outer tank, similar to the fabrication of tanks for water softeners[29]. Another method consists of constructing a thin steel shell with an internal plastic tank. The tank is fabricated by first constructing the steel exterior, injecting plastic powder within the steel shell, and then rotating the tank within a furnace, thereby, coating the interior with the plastic. The steel exterior serves as the primary structural support for the tank. It is approximately 1/16 in. (1.6 mm) thick while the plastic interior, 1/16 in. to c in. (1.6 mm to 3.2 mm) thick, provides a non-corrosive surface in addition to some structural support. In both types of plastic tanks, the lower heat conductivity of the plastic compared to steel reduces the amount of heat conducted through the tank wall to the insulation. Both of the plastic tank construction methods enable an improved process of insulating the tank bottom. In typical electric water heaters utilizing metal tanks, the metal of the tank wall extends below the bottom of the tank and acts as a support ring. This support ring has direct contact through the bottom jacket with the floor and provides a path for conduction heat losses to the floor. Since the plastic tanks are completely insulated, standby losses from the bottom of the tank are significantly reduced.

The “steel shell/plastic interior” tank was the plastic tank type modeled for this analysis as it is the least expensive to manufacture. In modeling this plastic tank type with WATSIM, the tank wall thickness and conductivity were modified to correspond to the plastic instead of steel. (The conductivity of the plastic/steel composition at the thickness levels described above is virtually identical to plastic.) In addition, the support ring material was changed from steel to foam insulation and the bottom insulation was increased to 1 in. (2.5 cm) of foam insulation. Table 13 summarizes the changes made to the analytic baseline model to simulate the performance of a plastic tank.

Table 13. Electric Water Heater Modeling Differences: Analytic Baseline Model vs. Plastic Tank*

Descriptive parameter	**Analytic Baseline**	**Plastic Tank**
tank:wall thickness	0.063 in. (0.16 cm)	steel 0.0853 in. (0.16 cm) plastic 0.126 in. (0.32 cm)
wall conductivity	0.40 BTU/ft·min·°F (41.54 W/m·K)	0.0018 BTU/ft·min·°F (0.1869 W/m·K)
support ring conductivity	0.40 BTU/ft·min·°F (41.54 W/m·K)	0.000236 BTU/ft·min·°F (0.024507 W/m·K)
tank insulation - thickness bottom:	0.75 in. (1.91 cm)	1.0 in. (2.54 cm)
tank insulation - conduct. bottom:	0.000333 BTU/ft·min·°F (0.0346 W/m·K)	0.000240 BTU/ft·min·°F (0.0249 W/m·K)

Note: * Units in the table are consistent with the units used by the WATSIM simulation model.

Design Option Manufacturer Costs

Manufacturer costs were primarily based upon data provided by GAMA with the exception of the plastic tank design option, which were provided by Max Minniear. The cost estimates were based upon the production of a 50 gallon (190 liter) electric water heater were disaggregated into variable (material, labor, transportation, overhead) and fixed (capital, product design) costs. Design option variable costs (from GAMA and Mr. Minniear) and fixed costs (from GAMA) were provided as a per unit cost and expressed as an incremental increase over the baseline design. The plastic tank design option fixed costs were provided as the “lump sum” amount required to convert the baseline production to the new design and the “lump sum” amount was converted to a per unit cost by amortizing it over a five year period and dividing it by Mr. Minniear’s assumed baseline model production volume of 40,000 units per year.

Existing Baseline Model. GAMA's existing baseline model cost estimates were based upon a water heater with 1½ in. (3.8 cm) of foamed jacket insulation using HCFC-141b as a blowing agent. For the other levels of insulation, the amount and cost of materials associated with varying thicknesses of HCFC-141b foam insulation were developed. Thus, the material costs associated with a particular level of insulation could easily be determined by either subtracting from or adding to GAMA's baseline costs. Table 14 summarizes the material costs associated with varying levels of foam insulation blown with HCFC-141b. The material costs of HCFC-141b foam insulation ($1/lb or $2.2/kg) and sheet metal ($0.30/lb or $0.66/kg) were based on estimates by Mr. Minniear[30].

Table 14. Existing Electric Water Heater Material Costs Associated with varying thicknesses of HCFC-141b Foam Insulation

Polyurethane Foam 141b				Jacket Sheet Metal				Misc	Total
thickness	**volume[1]**	**weight[2]**	**cost[3]**	**area**	**thickness**	**weight[4]**	**cost[5]**	**cost[6]**	**cost**
in. (cm)	*ft^3 (m^3)*	*lb (kg)*		*ft^2 (m^2)*	*ft^3 (m^3)*	*lb (kg)*			
1.0 (2.5)	1.83 (0.05)	3.65 (1.66)	$3.65	23.99 (2.23)	0.038 (0.001)	18.57 (8.42)	$5.57	$0.00	$9.23
1.5 (3.8)	2.84 (0.08)	5.68 (2.58)	$5.68	25.66 (2.38)	0.041 (0.001)	19.87 (9.01)	$5.96	$0.00	$11.64
2.0 (5.1)	3.92 (0.11)	7.84 (3.56)	$7.84	27.37 (2.54)	0.043 (0.001)	21.19 (9.61)	$6.35	$5.67	$19.86
2.5 (6.4)	5.07 (0.14)	10.14 (4.60)	$10.14	29.12 (2.71)	0.046 (0.001)	22.54 (10.22)	$6.76	$8.04	$24.94
3.0 (7.6)	6.29 (0.18)	12.59 (5.71)	$12.59	30.90 (2.87)	0.049 (0.001)	23.92 (10.85)	$7.18	$11.59	$31.35

[1] 50 gallon (190 liter) tank dimensions: diameter = 15.8 in. (40.1 cm), length = 54.5 in. (138.4 cm), dome height = 1.5 in. (3.8 cm)

[2] Foam density = 2 lb/ft^3 (32 kg/m^3)

[3] Foam cost = $1/lb ($2.2/kg)

[4] Sheet metal density = 489 lb/ft^3 (7833 kg/m^3)

[5] Sheet metal cost = $0.30/lb ($0.66/kg)

[6] Miscellaneous cost includes additional cost for dams to contain the insulation in a larger cavity during foaming.

Analytic Baseline Model. In order to convert the baseline manufacturer costs associated with foam insulation blown with HCFC-141b to that blown with HFC-245fa, the amount and cost of materials associated with varying thicknesses of HFC-245fa foam insulation were developed. Thus, the material costs associated with a particular level of HFC-245fa insulation could easily be determined by adding to the baseline costs associated with a comparable level of HCFC-141b foam insulation. Table 16 summarizes the material costs associated with varying levels of HFC-245fa foam insulation. The material costs of HFC-245fa foam insulation ($1.32/lb or $2.9/kg) were based on estimates by Allied Signal[31]. Table 15 shows the calculation of the total foam cost for HFC-141b and HFC-245fa foam insulation, based on the component cost estimates.

Table 15. Foam Components Cost Estimate

Foam Components	Fraction	Component Cost	Total Cost (141b)	Total Cost (245fa)
	%	$/lb	$/lb	$/lb
blowing agent (141b)	13.00%	$1.50	$0.20	-
blowing agent (245fa)	13.00%	$4.00	-	$0.52
isocyanurate	51.00%	$0.75	$0.38	$0.38
polyols	31.00%	$0.65	$0.20	$0.20
catalysts, refractants, etc.	5.00%	$4.50	$0.23	$0.23
Total	100.00%		**$1.00**	**$1.32**

Table 16. Analytic Electric Water Heater Material Costs Associated with varying thicknesses of HFC-245fa Foam Insulation

Polyurethane Foam 245fa				Jacket Sheet Metal				Misc	Total
thickness[1]	volume[2]	weight[3]	cost[4]	area	thickness[1]	weight[5]	cost[6]	cost[7]	cost
in. (cm)	*ft^3 (m^3)*	*lb (kg)*		*ft^2 (m^2)*	*ft^3 (m^3)*	*lb (kg)*			
1.0 (2.5)	1.83 (0.05)	3.65 (1.66)	$4.82	23.99 (2.23)	0.038 (0.001)	18.57 (8.42)	$5.57	$0.00	$10.39
1.55 (3.94)	2.95 (0.08)	5.90 (2.68)	$7.78	25.84 (2.40)	0.041 (0.001)	20.00 (9.07)	$6.00	$0.00	$13.78
2.0 (5.1)	3.92 (0.11)	7.84 (3.56)	$10.35	27.37 (2.54)	0.043 (0.001)	21.19 (9.61)	$6.35	$5.67	$22.37
2.5 (6.4)	5.07 (0.14)	10.14 (4.60)	$13.39	29.12 (2.71)	0.046 (0.001)	22.54 (10.22)	$6.76	$8.04	$28.19
3.0 (7.6)	6.29 (0.18)	12.59 (5.71)	$16.61	30.90 (2.87)	0.049 (0.001)	23.92 (10.85)	$7.18	$11.59	$35.38

[1] Thickness increased due to increased conductivity of 245fa relative to 141b.

[2] 50 gallon (190 liter) tank dimensions: diameter = 15.8 in. (40.1 cm), length = 54.5 in. (138.4 cm), dome height = 1.5 in. (3.8 cm)

[3] Foam density = 2 lb/ft^3 (32 kg/m^3)

[4] Foam cost = $1.32/lb ($2.9/kg)

[5] Sheet metal density = 489 lb/ft^3 (7833 kg/m^3)

[6] Sheet metal cost = $0.30/lb ($0.66/kg)

[7] Miscellaneous cost includes additional cost for dams to contain the insulation in a larger cavity during foaming.

As noted in Table 16, the actual thickness level for 1.5 in. (3.8 cm) of HFC-245fa foam insulation was assumed to be slightly greater than that for HCFC-141b foam insulation due to HFC-245fa's higher conductivity. For this analysis it was assumed that manufacturers would retain the same level of insulation thermal resistance for their baseline model when switching from HCFC-141b to HFC-245fa foam insulation.

Table 17 presents the manufacturer cost estimates for a 50 gallon (190 liter) electric water heater with 1½ in. (3.8 cm) of HCFC-141b foam insulation and the costs associated with the same baseline model foamed with HFC-245fa insulation. The material costs for the HCFC-141b baseline model were adjusted upward by the difference in material costs ($2.14) calculated between the HCFC-141b and HFC-245fa models.

Table 17. Electric Water Heater Baseline Model with HCFC-141b and HFC-245fa: Manufacturer Costs

Design	Variable Costs (per unit)				Fixed Costs (per unit)			Total Mfg Cost
	Material	Labor	Overhead	Total	Capital	Product Design	Total	
Baseline w/ 141b - 1.5 in (3.8 cm)	$62.16	$12.41	$50.99	$125.56	$0.00	$0.00	$0.00	$125.56
Baseline w/ 245fa - 1.55 in (3.94	$64.30	$12.41	$50.99	$127.70	$0.00	$0.00	$0.00	$127.70

Heat Traps. Manufacturer costs for metal and plastic heat traps were based upon data provided by GAMA. GAMA's data did not provide separate costs for metal and plastic heat traps. Data from the heat trap manufacturer Perfection, Inc.[32] was used as a reference. Metal heat trap material costs for both the supply and draw lines were based on a ¾-in. (1.9 cm) by 3-in. (7.6 cm) pipe nipple assembly design. Plastic heat trap material costs for the supply line were based on a plastic drop-in-tube design while those for the draw line were based on a plastic cartridge heat trap design within a combined outlet and anode rod assembly. Table 18 summarizes the incremental manufacturer costs for incorporating metal and plastic heat traps into an electric water heater. GAMA did not disagregate the capital cost and the product design cost but provided a total fixed cost. The costs reflect the addition of heat traps to both the supply and draw lines.

Table 18. Heat Traps for Analytic Electric Water Heaters: Incremental Manufacturer Costs

Design	Incremental Variable Costs (per unit)				Incremental Fixed Costs (per unit)			Total Incremental Mfg Cost
	Material	Labor	Overhead	Total	Capital	Product Design	Total	
Heat Traps (metal)	$2.59	$0.20	$0.83	$3.62	$0.00	$0.00	$0.39	$4.01
Heat Traps (plastic)	$2.59	$0.20	$0.83	$3.62	$0.00	$0.00	$0.39	$4.01

Note: 1) Perfection Inc.'s data was almost identical for both types ($3.00 for plastic and $2.95 for metal heat traps); 2) Note that GAMA's heat trap variable costs are different for electric water heaters and gas-fired water heaters.

Increased Jacket Insulation. Since the analytic baseline model for the Engineering Analysis assumes foam insulation based on HFC-245fa, manufacturer cost estimates for increases in the jacket insulation were based upon insulation blown with HFC-245fa. All foam cost data were based on information provided by Allied Signal. As presented earlier, Table 14 depicted the material costs for varying levels of HFC-245fa foam insulation. GAMA provided variable cost and fixed cost data for jacket insulation increases from a baseline level of 1.5 in. (3.81 cm) to a thickness of 2.0 in. (5.1 cm) only. In order to generate variable cost and fixed cost data for the next level of insulation, the data provided by M. Minniear was used to calculate ratios of variable and fixed cost for 2" insulation to 2.5" insulation. GAMA's costs for 2.0 in. (5.1 cm) insulation modified for 245fa blowing agent, were multiplied by those ratios to approximate the variable and fixed costs for 2.5 in. (6.4 cm) of insulation. Table 18 summarizes the incremental manufacturer costs for jacket insulation increases from a baseline level of 1.5 in. (3.81 cm) to a thickness of 2.0 in. (5.1 cm) and 2.5 in. (6.4 cm) (using material cost provided in Table 16). As stated earlier, insulation thicknesses were limited to 2½ in. (6.4 cm) due to installation and shipping concerns.

Table 19. Increased Jacket Insulation for Analytic Electric Water Heaters: Incremental Manufacturer Costs

Design	Incr. Variable Cost (per unit)				Incr. Fixed Costs (per unit)			Total Incremental Mfg Cost
	Material	Labor	Overhead	Total	Capital	Product Design	Total	
Incr. Insulation - 2.0 in (5.1 cm)	$8.59	$0.51	$3.66	$12.76	$0.00	$0.73	$0.73	$13.49
Incr. Insulation - 2.5 in (6.4 cm)	$14.41	$1.02	$7.32	$22.75	$0.00	$1.02	$1.02	$23.77

Insulating the Tank Bottom. Manufacturer costs for insulating the tank bottom were based on data from GAMA, which included total incremental variable cost and total fixed cost only. Table 20 summarizes the incremental manufacturing costs for insulating the tank bottom. The modeling of this design option is based on the following considerations: The bottom insulation is assumed to fill the entire space covered by the concave dome. Since the bottom insulation also consists of an c-in. (3.2 mm) foamed disk which the water heater "stands" on, the overall height of the water heater is increased by c of an in. (3.2 mm). It is important to note, that at this time no explanation of the design assumptions associated with insulating the tank bottom was provided by GAMA. Other sources (Max Minniear and Eugene West), provided an incremental total cost almost a magnitude lower than GAMA's. For comparison, Mr. Minniear's total manufacturing cost estimate is $4.25 and Mr. West's estimate for material cost only is $0.85.

Table 20. Insulating the Tank Bottom for Analytic Electric Water Heaters: Incremental Manufacturing Costs

Design	Incremental Variable Costs (per unit)				Incremental Fixed Costs (per unit)			Total Incremental Mfg Cost
	Material	Labor	Overhead	Total	Capital	Product Design	Total	
Insulate Tank Bottom	$0.00	$0.00	$0.00	$26.98	$0.00	$0.00	$3.39	$30.37

Plastic Tank. Manufacturer costs for a plastic tank electric storage water heater design were based on data provided by Mr. Minniear. The plastic tank design is based on the "steel shell/ plastic interior" tank type discussed earlier and assumes a tank wall thickness of 0.20 in. (5.1 mm). Table 21 summarizes the incremental manufacturer costs for switching from a metal tank to a plastic tank design.

Table 21. Plastic Tank Design for Electric Water Heaters: Incremental Manufacturer Costs

Design	Incremental Variable Costs (per unit)				Incremental Fixed Costs (per unit)			Total Incremental Mfg Cost
	Material	Labor	Overhead	Total	Capital	Product Design	Total	
Plastic Tank	$5.25	$0.80	$3.20	$9.25	$15.00	$3.00	$18.00	$27.25

Design Option Retail Prices

For purposes of this analysis, the retail price is considered to be the cost to the consumer of only the water heating equipment. The cost to the consumer of installing the water heater (i.e., the installation cost) is not considered to be part of the retail price and is discussed later.

The retail price for a baseline 50-gallon (190 liter) electric storage water heater (with HCFC-141b foam insulation) was determined by contacting various plumbing contractors and large retail chains. Since the price of a water heater is a function of the length of the manufacturer's warranty, only water heaters warrantied for 5 years were considered as baseline models. The 5 year warranty is the shortest warranty period offered by water heater manufacturers (although a 1 year warranty is offered in special cases) and is typically reserved for those models which are produced in large volumes (i.e., baseline models). A longer warranty time period, in addition to raising the price, may indicate the presence of design feature not normally found in baseline models. Table 22 provides the list of retail prices used to develope the retail price of the baseline model. For each price listed, the source is also provided. All data presented in Table 22 are from the LBNL Water Heater Database[33].

Table 22. 50-Gallon (190 liter) Electric Storage Water Heater Retail Prices

Source	Manufacturer	Brand	Model	Retail
Denver, CO	State Industries	Reliance	5-52-2ORT	$128.00
Dale City, VA	American Water Heaters	Craftsman		$128.00
Atlanta, GA	American Water Heaters	PROLine	E52-50R-045DV	$129.00
Atlanta, GA	American Water Heaters	PROLine	E52-50R-045DV	$135.00
Stockbridge, GA	American Water Heaters	Envirotemp	E52-50R-045DV	$138.00
Marieeta, GA	American Water Heaters	Envirotemp	E52-50R-045DV	$138.00
Charlotte, NC	American Water Heaters	More-Flo	E52-50R-045DV	$141.00
Dallas, TX	State Industries	Reliance	5-52-2ORT	$146.00
West Allis, WI	American Water Heaters	American		$147.00
Chicago, IL	American Water Heaters	More-Flo	E52-50R-045DV	$148.00
Minneapolis, MN	American Water Heaters	More-Flo	E52-50R-045DV	$148.00
SW Jackson, MS	American Water Heaters	American	E52-50R-045DV	$149.00
Lexington, KY	American Water Heaters	American	E52-50R-045DV	$149.00
New Orleans, LA	American Water Heaters	American	E52-50R-045DV	$149.00
Jacksonville, FL	A.O. Smith	Energy Saver	EES-52	$152.00

Source	Manufacturer	Brand	Model	Retail
Nashville, TN	American Water Heaters	American	E52-50R-045DV	$157.00
St. Louis, MO	American Water Heaters	American	E52-50R-045DV	$160.00
Kilgore, TX	A.O. Smith	Energy Saver	FSG-50	$163.00
Salt Lake City, UT	American Water Heaters	American	E52-50R-045DV	$168.00
Denver, CO	State Industries	Reliance	5-52-2ORT	$168.00
Reno, NV	American Water Heaters	American	E52-50R-045DV	$168.00
Harrisonburg, VA	State Industries		SCD-552-2ORT	$170.00
Richmond, CA	Sears/State Industries	Kenmore	31256	$170.00
Charlotte, NC	American Water Heaters			$171.00
Sacramento, CA	American Water Heaters	American	E52-50R-045DV	$172.00
Seattle, WA	State Industries	Reliance	5-52-2ORT	$175.00
Nashville, TN	American Water Heaters	American	E52-50R-045DV	$177.00
Winchester, VA	Rheem	Rheem	81V52D	$178.00
Phoenix, AZ	State Industries	Reliance	5-52-2ORT	$179.00
Las Vegas, NV	State Industries	Reliance	5-52-WORT	$179.00
Fredericksburg, VA	State Industries		CD5-52-2ORT	$180.00
Corpus Christy, TX	Rheem	Standard	81V52D	$180.00
Boise, ID	State Industries	Reliance	5-52-2KRT	$183.00
Boise, ID	State Industries	Reliance	5-52-2ORT	$184.00
Oklahoma City, OK	State Industries	Reliance	5-52-2ORT	$187.00
St. Louis, MO	American Water Heaters	American	E52-50R-045DV	$189.00
Boston, MA	State Industries	Powermiser 5	31256	$190.00
Indianapolis, IN	State Industries		CD6-52-2ORT	$197.00
Salt Lake City, UT	American Water Heaters	American	E52-50R-045DV	$198.00
Boston, MA	State Industries	Powermiser 5	31256	$200.00
Livermore, CA	Sears/State Industries	Kenmore		$200.00
Charlottesville, VA	Rheem	Ruud	PE52	$208.00
Boise, ID	State Industries	Reliance	5-52-2KRT	$208.00
Berkeley, CA	Rheem	Rheem	81V52D	$227.00
Anchorage, AK	Bradford White			$231.00
Tampa, FL	Rheem	Standard	81V50D	$234.00
Berkeley, CA	Rheem	Rheem	81SV52D	$239.00
Boston, MA	State Industries	Anniv. Series 10		$250.00
Bristow, VA	Rheem	Rheem	81V52D	$282.00
Boise, ID	State Industries	Reliance	5-52-2KRT	$297.00
Average Retail Cost				**$178.88**

As listed in Table 22, the average retail price for a baseline 50 gallon (190 liter) electric storage water heater was $178.88 (without taxes). As presented earlier, the manufacturer cost of any existing baseline water heater is $125.56. Using the average national value for taxes of 5.20% (developed by A.D.L, 1998), yields a retail price of $188.18. Dividing the retail price ($188.18) by the manufacturer cost ($125.56) it yields a manufacturer cost-to-retail price markup of 1.50 (an exact value of 1.49874 is used as a multiplier).

The baseline manufacturer cost-to-retail price markup was assumed constant for all design options considered for this analysis. Thus, the retail price for any modified design was simply determined by multiplying the manufacturer cost by the derived markup of 1.50.

Installation and Maintenance Costs

The installation cost is the cost to the consumer of installing the water heater and is not considered part of the retail price. The cost of installation covers all labor and material costs associated with the simple replacement of an existing water heater. Delivery, removal, and permit fees are also included.

LBNL collected data to establish the installation cost of a 50 gallon (190 liter) baseline electric storage water heater from the same sources that the retail price data was obtained. Table 23 lists the installation costs for the water heater models. The average installation cost was $160.73. None of the design options considered for this analysis increased the installation cost of a baseline electric storage water heater. All data presented in Table 23 are from the LBNL Water Heater Database[34].

Table 23. 50-Gallon (190 liter) Electric Storage Water Heater Installation Costs

Source	Manufacturer	Brand	Model	Installation
Berkeley, CA	Rheem	Rheem	81SV52D	$65.00
Berkeley, CA	Rheem	Rheem	81V52D	$65.00
Boise, ID	State Industries	Reliance	5-52-2KRT	$114.00
Boise, ID	State Industries	Reliance	5-52-2KRT	$114.00
Boise, ID	State Industries	Reliance	5-52-2KRT	$114.00
Boise, ID	State Industries	Reliance	5-52-2KRT	$114.00
Stockbridge, GA	American Water Heaters	Envirotemp	E52-50R-045DV	$119.00
Salt Lake City, UT	American Water Heaters	American	E52-50R-045DV	$125.00
Salt Lake City, UT	American Water Heaters	American	E52-50R-045DV	$125.00
Denver, CO	State Industries	Reliance	5-52-2ORT	$130.00
Denver, CO	State Industries	Reliance	5-52-2ORT	$130.00
SW Jackson, MS	American Water Heaters	American	E52-50R-045DV	$135.00
Phoenix, AZ	State Industries	Reliance	5-52-2ORT	$136.00
Atlanta, GA	American Water Heaters	PROLine	E52-50R-045DV	$142.00
Nashville, TN	American Water Heaters	American	E52-50R-045DV	$145.00
Nashville, TN	American Water Heaters	American	E52-50R-045DV	$145.00
Charlotte, NC	American Water Heaters	More-Flo	E52-50R-045DV	$145.00
Marieeta, GA	American Water Heaters	Envirotemp	E52-50R-045DV	$149.00
Reno, NV	American Water Heaters	American	E52-50R-045DV	$154.00
Charlotte, NC	American Water Heaters			$155.00
Dallas, TX	State Industries	Reliance	5-52-2ORT	$155.00
West Allis, WI	American Water Heaters	American		$159.00
St. Louis, MO	American Water Heaters	American	E52-50R-045DV	$160.00
St. Louis, MO	American Water Heaters	American	E52-50R-045DV	$160.00

Source	Manufacturer	Brand	Model	Installation
Dale City, VA	American Water Heaters	Craftsman		$169.00
Springfield, VA	Rheem	Rheem	81V52D	$170.00
Springfield, VA	A.O. Smith	A.O. Smith	EES52	$170.00
Las Vegas, NV	State Industries	Reliance	5-52-2ORT	$170.00
Richmond, CA	Sears/State Industries	Kenmore	31256	$174.00
Tampa, FL	Rheem	Standard	81V50D	$175.00
Oklahoma City, OK	State Industries	Reliance	5-52-2ORT	$180.00
Lexington, KY	American Water Heaters	American	E52-50R-045DV	$200.00
Chicago, IL	American Water Heaters	More-Flo	E52-50R-045DV	$209.00
Sacramento, CA	American Water Heaters	American	E52-50R-045DV	$210.00
Boston, MA	State Industries	Anniv. Series 10		$220.00
Boston, MA	State Industries	Powermiser 5	31256	$220.00
Boston, MA	State Industries	Powermiser 5	31256	$220.00
New Orleans, LA	American Water Heaters	American	E52-50R-045DV	$225.00
Seattle, WA	State Industries	Reliance	5-52-2ORT	$231.00
Atlanta, GA	American Water Heaters	PROLine	E52-50R-045DV	$234.00
Minneapolis, MN	American Water Heaters	More-Flo	E52-50R-045DV	$258.00
Average Installation Cost				**$160.73**

Information gathered to date suggests that there is virtually no maintenance of residential electric water heaters, although manufacturers recommend they be drained and flushed annually to minimize deposition of sediment, maintain operating efficiency and prolong equipment life. Thus, maintenance costs were not developed for the baseline model. The design options considered for this analysis were assumed not to increase the maintenance cost of electric water heaters.

Cost-Efficiency Data

The results of the design option analysis for 50 gallon (190 liter) electric storage water heaters are presented in Table 24. Included in the cost-efficiency table are the following: disaggregated manufacturer costs, retail prices, installation costs, maintenance costs, energy factor, energy use, and payback periods. Design options were added incrementally to the baseline model in order of shortest payback period. The payback period for each set of design options was calculated relative to the baseline design according to the following relationship:

$$PAYBACK = \frac{\Delta CC}{\Delta OC} = \frac{\Delta RC + \Delta IC}{\Delta EC + \Delta MC}$$

where;

$PAYBACK$ = payback period (years),
ΔCC = change in consumer cost relative to baseline, ($),
ΔOC = change in operating cost relative to baseline, ($/year),
ΔRC = change in retail cost relative to baseline, ($),

ΔIC = change in installation cost relative to baseline, ($),
ΔEC = change in energy cost relative to baseline, and ($/year),
ΔMC = change in annualized maintenance cost relative to baseline, ($/year).

The existing baseline design with HCFC-141b foam insulation is presented in Table 24 to show the manufacturer cost and retail price differences between the baseline designs with HCFC-141b and HFC-245fa. For purposes of this analysis, the cost effectiveness of all design options were evaluated relative to the analytic baseline design with HFC-245fa. Energy costs were from national average energy prices for the year 2003 from the *1998 Annual Energy Outlook* [35].

Metal heat traps are not included in the cost/efficiency table because plastic heat traps are more cost effective. The highest EF attainable is 0.908 which can be achieved through the use of plastic heat traps, 2½ in. (6.4 cm) of jacket insulation, and a plastic tank. The payback period of this design is just over 4 years and there are 238 kWh/yr energy savings. Electric water heaters incorporating plastic heat traps, 2.5 in. of insulation and tank bottom insulation have a payback of 4.6 years. This design saves 233 kWh/yr in electricity.

As described earlier in this report, the EF and other parameters of the water heater, such as the RE, were determined from output generated by the WATSIM simulation model and the DOE test procedure equations. It is interesting to note that the recovery efficiencies calculated in this manner for the baseline model and design options and reported in Table 24 are less than the 98% RE default permitted by the DOE test procedure.

Figure 1 graphically depicts the relationship between both increased consumer cost and increased operating cost versus EF.

Table 24. Cost-Efficiency Table for 50 gallon (190 liter) Electric Storage Water Heaters

Design No.	Design Options	Incremental Variable Costs [1,2] Mat'l	Labor	Overhd	Total Var.	Incremental Fixed Costs Capita	Product Design	Total Fixed	Total Mfg Cost	Retail Price[1,5]	Install. Cost[1]	Maint. Cost[1]	Energy Factor	Recov. Eff.	UA	Energy Use Daily *kWh/day*	Yearly *kWh/yr*	Payback Period [4] *years*
0	Existing Baseline (141b) - 1.5" (3.8 cm) [3]	$62.16	$12.41	$50.99	$125.56	$0.00	$0.00	$0.00	$125.56	$188.18	$160.73	$0.00	0.858	96.69%	3.64	13.60	4965	NA
0a	Analytic Baseline (245fa) - 1.5" (3.8 cm)	$2.14	$0.00	$0.00	$2.14	$0.00	$0.00	$0.00	$127.70	$191.39	$160.73	$0.00	0.858	96.69%	3.64	13.60	4965	NA
1	0a + Heat Traps (plastic)	$2.59	$0.20	$0.83	$3.62	$0.00	$0.39	$0.39	$131.71	$197.40	$160.73	$0.00	0.876	97.02%	3.06	13.36	4875	0.85
2	1 + Incr. Insulation to 2" (5.1 cm)	$8.59	$0.51	$3.66	$12.76	$0.00	$0.73	$0.73	$145.20	$217.62	$160.73	$0.00	0.890	97.17%	2.62	13.17	4805	2.08
3	1 + Incr. Insulation to 2.5" (6.4 cm)	$14.41	$1.02	$7.32	$22.75	$0.0	$1.02	$1.02	$155.48	$233.02	$160.73	$0.00	0.901	97.27%	2.29	13.03	4755	2.52
4	3 + Plastic Tank[4]	$5.25	$0.80	$3.20	$9.25	$15.00	$3.00	$18.00	$182.73	$273.86	$160.73	$0.00	0.908	97.03%	2.06	12.95	4727	4.40
5	3 + Insulate Bottom	$0.00	$0.00	$0.00	$26.98	$0.00	$0.00	$3.39	$185.85	$278.54	$160.73	$0.00	0.908	97.27%	2.13	12.97	4732	4.76

[1] All costs and prices in 1998$.

[2] Incremental variable and fixed costs are per unit costs.

[3] For the Baseline Model with HCFC-141b, the TOTAL variable costs are provided.

[4] Annual operating cost for Payback Period calculation established with an electricity price of 0.0787 $/kWh in 1998$.

[5] Retail Prices are calculated based on the Manufacturer to Retail Markup of 1.49874.

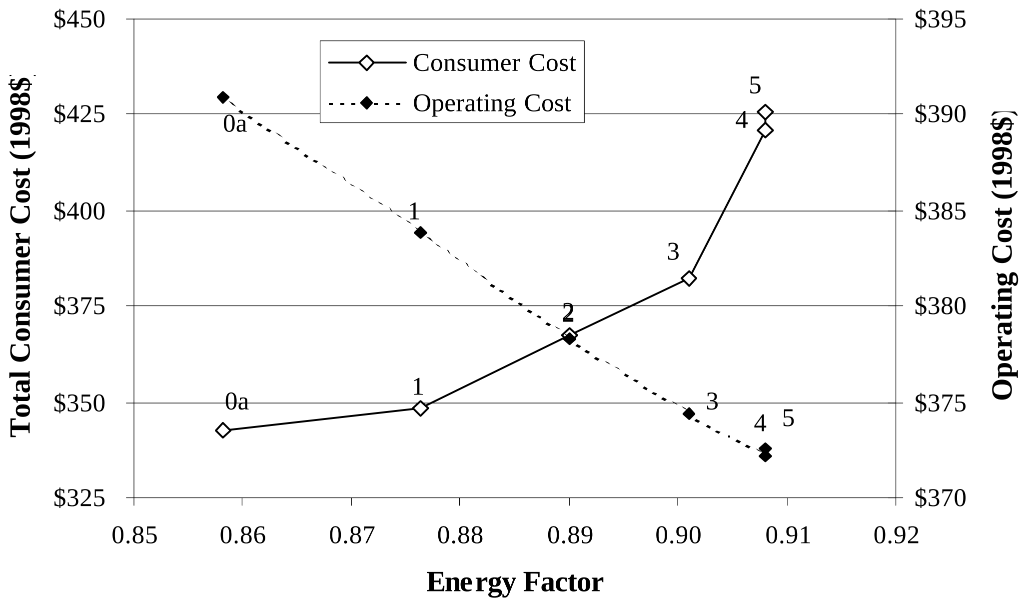

Figure 1. 50 gallon (190 liter) Electric Storage Water Heaters: Total Consumer Cost and Operating Cost vs. Energy Factor

GAS-FIRED WATER HEATERS

The Engineering Analysis models the design options for gas-fired water heaters using TANK, a computer simulation model for water heaters developed by Battelle for GRI. A 40 gallon (150 liter) nominal volume gas-fired water heater was used as the baseline model for this analysis.

Existing Typical Baseline model

In using TANK to establish the baseline model, the goal was to establish the characteristics of a 40 gallon (150 liter) baseline gas-fired water heater with HCFC-141b foam insulation which would yield a 0.54 EF (the minimum EF allowed by NAECA) and a RE close to 76%.

From information in GAMA's directory of certified water heaters and product literature from various manufacturers, it was determined that models of 40 gallon (150 liter) gas-fired water heaters achieved 0.54 EFs through the use of 1 in. (2.5 cm) foam insulation only (heat traps were not necessary). The input rating varied between 34,000 and 40,000 Btu/hr (10,000 to 11,700 W).

As a result of preliminary simulation work, it was determined that EFs close to 0.54 could only be achieved with input ratings of 40,000 Btu/hr (11,700 W) and flue diameters of 4 in. (10 cm). Thus, the baseline model was established with the following "general" characteristics: input rating of 40,000 Btu/hr (11,700 W), flue diameter of 4 in. (10.2 cm), 1 in. (2.5 cm) of foam insulation, and no heat traps.

In developing the baseline model, Battelle was consulted because it had conducted simulations to characterize baseline gas-fired water heaters. Battelle's initial results were presented to a meeting of GRI's Water Heater Technical Advisory Group (TAG) in November, 1997 and are depicted in Table 25. Of Battelle's baseline characteristics, the input rating (39,630 Btu/hr (11614 W)), insulation thickness (0.981 in. (2.492 cm)), flue diameter (4 in. (10.2 cm)), and heat traps (none) are virtually identical to the "general" baseline characteristics stated above. With regard to the insulation thickness, Battelle measurements revealed that insulation thicknesses in gas-fired water heaters are actually slightly less than the nominal values (e.g., a "1 in." nominal thickness is actually 0.981 in. (2.492 cm)).

Table 25. Battelle Baseline Model Characteristics as presented at November 1997 GRI TAG meeting

Parameter	**Value**
Input Rating	39630 Btu/hr (11614 W)
Pilot Input	400 Btu/hr (117 W)
Excess Combustion Air (%)	39.0
Pressurized Tank Dimensions	
Inside Diameter	15.84 in. (40.23 cm)
Steel Wall Thickness	0.08 in. (0.20 cm)
Height	47.6 in. (120.9 cm)
Volume	38.0 gallons (143.8 liter)
Jacket Description	
Foam insulation thickness	0.981 in. (2.492 cm)
Sheet metal thickness	0.019 in. (0.483 mm)
Thermal conductivity of foamed assembly	0.0155 Btu/hr·ft·°F (0.0268 W/m·K)
Off-cycle pressure loss coefficient	13.0042
Flue baffle effectiveness multiplier	1.896
Flue diameter	4.0 in. (10.2 cm)
Recovery efficiency (RE) (%)	75.0
Energy factor (EF)	0.54

From discussions with Battelle[36], it was learned that three input variables, the excess combustion air, the flue baffle effectiveness multiplier, and the off-cycle pressure loss coefficient, were varied in an attempt to achieve both a 0.54 EF and a 76% RE. In varying the above three input variables, Battelle was able to arrive at an EF of 0.54 but a RE of only 75%.

Because a 76% RE was not achieved with Battelle's baseline specifications, additional simulations were conducted to try to develop a 0.54 EF and 76% RE baseline. Feed-through losses were kept the same for electric and gas-fired water heaters. In addition, the same conductivities were specified for the jacket insulation for both the existing baseline gas and electric water heaters.

The excess combustion air, flue baffle effectiveness multiplier, and the off-cycle pressure loss coefficient are not independent of each other and cannot be varied independently to arrive at the desired EF and RE values. The off-cycle pressure loss coefficient can be expressed as a function of both the flue baffle effectiveness multiplier and excess combustion air. In turn, the EF and RE can also be expressed as functions of flue baffle effectiveness multiplier and excess combustion air (for a given set of input characteristics). Figure 2 depicts the variation of EF and RE with excess combustion air and flue baffle effectiveness multiplier. As Figure 2 demonstrates, 0.54 EFs and 76% REs occur at different sets of excess combustion air and flue baffle effectiveness multiplier values.

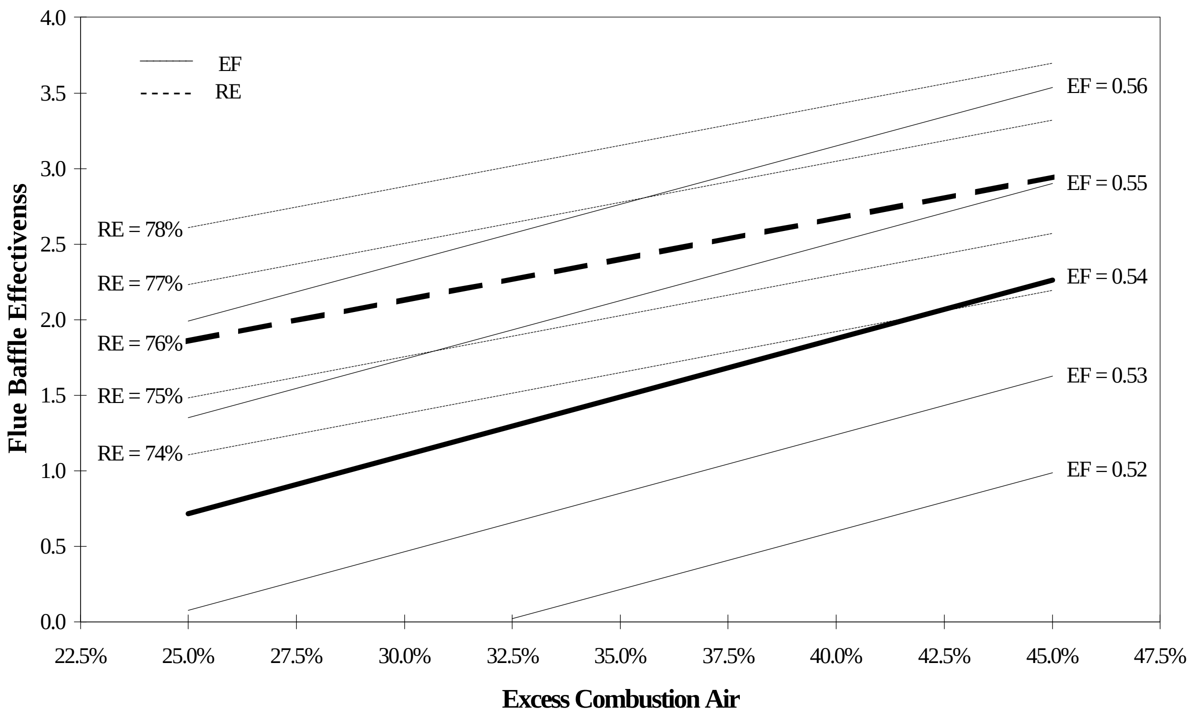

Figure 2. Energy Factor and Recovery Efficiency vs. Flue Baffle Effectiveness and Excess Combustion Air

Based on the above results, other TANK input variables were investigated as a means of increasing RE (without significantly impacting EF) or decreasing EF (without significantly impacting RE). Table 26 indicates the TANK input variables which were investigated. The acceptable range provided for the combustion chamber inner wall thickness, the flue wall thickness, the flue baffle thickness, the thermostat R-value, the skirt insulation, and the tank, flue, and flue baffle emissivities were based on what seemed to be reasonable values for these variables. The off-cycle pressure loss coefficient is not provided in Table 26 as it is dependent on the flue baffle effectiveness and the excess combustion air and is calculated by TANK .

Table 26. TANK Input Variables: Approximate Impact on EF and RE

Input Variable	**TANK Default**	**Acceptable Range**	**Impact on EF and RE**
Flue Baffle Effectiveness	1.896	1.2 - 2.0	Increase causes increased EF and RE
Excess Combustion Air	32%	25% - 70%	Increase causes decreased EF and RE
Pressure Vessel Wall Thickness - *in (cm)*	0.08 (0.20)	> 0.05 (> 0.13)	Decrease causes small RE incr., small EF decr
Combustion Chamber Height - *in (cm)*	8.5 (21.6)	7.5-9.5 (19.1-24.1)	Decrease causes incr'd RE; low impact on EF
Comb. Chamber Inner Wall Thick. - *in (cm)*	0.04 (0.10)	> 0.03 (>0.08)	Decrease causes incr'd RE; low impact on EF
Multiplier for Dome-Shaped Comb. Chamber	1.15	1.00 - 1.30	Increase causes incr'd EF and RE; larger RE incr
Flue Wall Thickness - *in (cm)*	0.08 (0.20)	> 0.05 (>0.13)	Increase causes small RE incr.; no impact on EF
Flue Baffle Thickness - *in (cm)*	0.063 (0.16)	> 0.04 (> 0.10)	Increase causes incr'd RE; low impact on EF
R-value T'stat Fitting - *hr·ft^2·°F/Btu (K·m2/W)*	0.10 (0.02)	0.05-0.10 (0.01-0.02)	Decrease causes small EF decr; no impact on RE
Skirt Insul. Conduct - *Btu/hr-ft-°F (W/m2·K)*	0.03 (0.05)	0.02-0.04 (0.03-0.07)	Increase causes decr'd EF and RE; larger EF decr
Emissivity for Tank, Flue, and Flue Baffle	0.95	< 0.97	Decrease causes decr'd EF & RE; larger RE decr

Starting with a flue baffle effectiveness (2.0) and excess combustion air (40%) that yielded an EF close to 0.54 and as high an RE as possible, the above input variables were adjusted in an attempt to increase the RE to 76% without significantly increasing the EF. In order to realize an EF and RE within a half a percentage point of the desired values, some of the input variables had to be set beyond their acceptable range. Table 27 provides the values of the above input variables that were used to arrive at acceptable EF and RE values. Input values in Table 27 appearing in bold font, the combustion chamber height, the combustion chamber inner wall thickness, the flue baffle thickness, and the skirt insulation conductivity, were the only variables set beyond their acceptable limits. Although their limits were exceeded, none went significantly beyond the acceptable range. This set parameters may not match the physical characteristics of the actual water heaters, but do allow the simulation model to predict the expected level of energy consumption, EF and RE.

Table 27. TANK Input Values providing acceptable EF and RE values

Input Variable	Value Used	Acceptable Range
Flue Baffle Effectiveness	2.0	1.2 - 2.0
Excess Combustion Air	42%	25% - 70%
Pressure Vessel Wall Thickness - *in. (cm)*	0.054 (0.137)	> 0.05 (> 0.13)
Combustion Chamber Height - *in. (cm)*	**6.5 (16.5)**[1]	7.5 - 9.5 (19.1 - 24.1)
Comb. Chamb. Inner Wall Thick. - *in. (cm)*	**0.01 (0.025)**[1]	> 0.03 (> 0.08)
Multiplier for Dome-Shaped Comb. Chamber	1.25	1.00 - 1.30
Flue Wall Thickness - *in. (cm)*	0.05 (0.13)	> 0.05 (> 0.13)
Flue Baffle Thickness - *in. (cm)*	**0.03 (0.076)**[1]	> 0.04 (> 0.10)
R-value for Thermostat Fitting - *hr·ft^2·°F/Btu (K·m^2/W)*	0.05 (0.01)	0.05 - 0.10 (0.01 - 0.02)
Skirt Insulation Conductivity - *Btu/hr·ft·°F (W/m·K)*	**0.042 (0.073)**[1]	0.02 - 0.04 (0.03 - 0.07)
Emissivity for Tank, Flue, and Flue Baffle	0.95	< 0.97

[1] Value used is outside of acceptable range.

The above input variables yielded a 0.5446 EF and a 75.5% RE. Table 28 summarizes the primary baseline characteristics. Note that the conductivity of the jacket insulation was changed from the TANK default value to match that being used in the baseline electric water heater model. The values in Table 28 describe the water heater in engineering terms used by TANK.

Table 28. Gas-Fired Water Heater Baseline Model Characteristics

Descriptive parameter	Value
Input Rating	40000 Btu/hr (11723 W)
Pilot Input	400 Btu/hr (117 W)
On-cycle power consumption	0.0 W
Off-cycle power consumption	0.0 W
Excess Combustion Air	42.0 (%)
Off-cycle pressure loss coefficient	12.4047
Flue baffle effectiveness multiplier	2.000
Natural Gas - Higher Heating Value	1028 Btu/scf (38302 kJ/m^3)
Pressurized Tank Dimensions	
Inside Diameter	15.892 in. (40.366 cm)
Steel Wall Thickness	0.054 in. (0.1372 cm)
Height	47.6 in. (120.9 cm)
Volume	38.0 gallons (143.8 liter)
Jacket Description	
Foam insulation thickness	0.981 in. (2.492 cm)
Sheet metal thickness	0.019 in. (0.0483 cm)
Thermal conductivity of foamed assembly	0.0140 Btu/hr·ft·°F (0.0242 W/m·K)

Outer Jacket Emissivity	0.92
Flue Description	
Internal Diameter	4.00 in. (10.16 cm)
Area Fraction for Upflow	0.066
Flue Wall Thickness	0.050 in. (0.127 cm)
Flue Baffle Emissivity	0.95
Flue Baffle Thickness	0.030 in. (0.0762 cm)
Combustion Chamber Description	
Skirt Insulation Thermal Conductivity	0.042 Btu/hr·ft·°F (0.073 W/m·K)
Chamber Height	6.5 in. (16.5 cm)
Chamber Inner Wall Thickness	0.010 in. (0.0254 cm)
Flame Radiation View Factor to Skirt	0.2
Distance between Burner and Fire Entrance	4.00 in. (10.16 cm)
Dome Heat Transfer Area Multiplier	1.25
Pipes and Fittings	
Heat Traps (0 - none, 1 - metal, -1 - plastic)	0
Supply and Draw Pipe Inside Diameter	0.785 in. (1.994 cm)
Pressure Relief Valve Exposed Area	18.0 in^2 (116.1 cm^2)
Drain Valve Exposed Area	9.0 in^2 (58.1 cm^2)
Thermostat Exposed Area	9.0 in^2 (58.1 cm^2)
Anode Rod Fittings Exposed Area	0.0 in^2 (0.0 cm^2)
Volume to Thermostat	4.05 gallons (15.33 liter)

Modeling Design Options

Table 1 shows the seven design options which are being considered to improve the efficiency of gas-fired storage water heaters. Each design option is briefly discussed below along with the methodology of how it was analyzed with TANK . TANK determines the pressure loss coefficient based on the water heater's characteristics. Although the pressure loss coefficient is primarily dependent on the excess combustion air and the flue baffle effectiveness multiplier, any water heater characteristic can effect the off-cycle pressure loss coefficient. Thus, before a TANK simulation run was conducted for a design option, the off-cycle pressure loss coefficient was determined with TANK based on the characteristics of the water heater. After the off-cycle pressure loss coefficient was established, it was specified as one of the water heater's characteristics and TANK was used to model the water heater's performance. For some design options, such as heat traps and increased jacket insulation, there was little impact on the off-cycle pressure loss coefficient but the improved flue baffle design option had a significant effect on the off-cycle pressure loss coefficient.

The side-arm heater was the only design option not modeled with TANK. Because TANK is not able to model side-arm heaters, the WHAM energy calculation method was used to estimate efficiency improvement of this design option.

Analytical Baseline Model. The existing baseline model's HCFC-141b foam insulation was replaced with HFC-245fa foam insulation due to the impending phase out of HCFC-141b in the year 2003. According to the Bayer report, HFC-245fa has a 3.0% higher conductivity than HCFC-141b - see Table 4. Thus, the conductivity value of the foam insulation in the baseline model listed in Table 26 was increased by 3.0% to a value of 0.0144 Btu/hr·ft·°F (0.0249 W/m·K). In addition, the thickness of the foam insulation surrounding the tank was increased from 0.981 in. (2.492 cm) to 1.00 in. (2.54 cm) to compensate for the insulation's increased conductivity. This increase in insulation thickness also resulted in an increase of jacket material. Table 29 summarizes the changes that were made to the existing baseline model with HCFC-141b in order to simulate its performance with HFC-245fa.

Table 29. Gas-Fired Water Heater Modeling Differences: Existing Baseline Model vs. Analytic Baseline Model

Descriptive parameter	Existing Baseline	Analytic Baseline
Jacket Description		
Foam insulation thickness	0.981 in. (2.492 cm)	1.000 in. (2.540 cm)
Thermal conductivity of foamed assembly	0.0140 Btu/hr·ft·°F (0.0242 W/m·K)	0.0144 Btu/hr·ft·°F (0.0249 W/m·K)

Heat Traps. Metal and plastic heat traps were analyzed for gas-fired storage water heaters. Both types of heat traps prevent the losses associated with the circulation of hot water into the plumbing.

To simulate the performance of heat traps using TANK, the input variable designating the presence of heat traps simply needs to be specified with a value of 1 for metal heat traps or -1 for plastic heat traps. Table 30 summarizes the changes made to the analytic baseline model in order to simulate the performance of metal and plastic heat traps.

Table 30. Gas-Fired Water Heater Modeling Differences: Analytic Baseline Model vs. Models with Metal and Plastic Heat Traps

Descriptive parameter	Analytic Baseline	with Metal Heat Traps	with Plastic Heat Traps
Pipes and Fittings			
Heat Traps (0 - none, 1 - metal, -1 - plastic)	0	1	-1

Increased Jacket Insulation. Most gas-fired water heaters on the market today have at least 1-in. (2.5 cm) thick polyurethane foam insulation, while some manufacturers provide 2- or 3-in. (5.1 or 7.6 cm) thick insulation, as well. Although increasing the insulation thickness reduces the standby loss, the increase in the overall diameter of the water heater may pose some installation problems. There will also be an increase in shipping costs because fewer heaters will fit in a truck. Because of these potential installation problems, maximum insulation thicknesses were limited to 2½ in. (6.4 cm) for this analysis.

Table 31 summarizes the changes made to the analytic baseline model to simulate the performance of a gas-fired water heater insulated with nominal thicknesses of "2-in." (1.981 in. (5.032 cm)) and "2½-in." (2.481 in. (6.302 cm)) of foam insulation.

Table 31. Gas-Fired Water Heater Modeling Differences: Analytic Baseline Model vs. Models w/ 2 & 2½ nominal in. of foam insulation

Descriptive parameter	Analytic Baseline	with 2 in. of foam insulation	with 2½ in. of foam insulation
Jacket Description			
Foam insulation thickness	1.000 in. (2.540 cm)	1.981 in. (5.032 cm)	2.481 in. (6.302 cm)

Improved Flue Baffle. The standard flue baffle is a twisted strip of metal inserted into the flue. It increases the turbulence of flue gases and improves heat transfer to the walls of the flue. The geometry of the flue baffle can be modified to increase its effectiveness.

A research project funded by GRI reviewed technical literature, manufacturers' literature, and patents to determine what new technologies are applicable to heat exchangers that involve flue gases from combustion of natural gas[37]. The conclusion was that significant increases in the convective heat transfer coefficient could be achieved with the use of heat transfer enhancement devices. The study suggested that in some cases, an increase in heat transfer coefficient might be accompanied by an increase in the pressure drop (due to an increase in the friction factor). The study identified twisted-tape inserts as a potential heat transfer enhancement device for water heaters.

Burners in fuel-fired water heaters are placed below the storage tank, with the flue extending up through the center of the tank to a draft hood. The combustion products enter the flue tube at a very high temperature (approximately 2300°F (1260°C)) and transfer heat by convection and radiation to the tube wall, and then by conduction to the water. When a baffle, such as a flat plate, is inserted in the flue, increased heat transfer occurs from the hot combustion products to the flue wall. The increase in the heat transfer is even greater when a twisted baffle tape is inserted in the flueway of a water heater. The twisted tape augments the convective heat transfer from the flue gases to the wall surfaces. In addition, the hot tape transfers heat to the water-tube walls by radiation.

Beckermann and Goldschmidt[38] investigated experimentally and empirically the effects of velocity of the flue gases, the twist (i.e., number of turns) of the tape, and the surface emissivities on the total heat transfer (convection and radiation) in a fuel-fired water heater. They reported that compared to an empty tube, the flue tube with twisted tape enhances the overall heat transfer performance by as much as 50%.

An improved flue baffle can increase the RE to about 78-85%, depending on the specific geometry. At the upper end of the RE range, the water heater would require power venting or induced draft and corrosion resistant flues for safe operation.

In addition to an increase in RE, improved flue baffles also reduce standby loss. The off-cycle standby loss is reduced by the additional restrictions to airflow due to the increased baffling. But because the enhanced or increased flue baffling increases pressure drop across the flue, the combustion products may have to be forced through the flue with a fan or blower. Venting combustion products through a horizontal venting system also requires a fan or blower. When the blower forces fresh air into the chamber, the configuration is called a forced draft system. By contrast, when the blower is located in the flue-gas exit, the configuration is called an induced draft system. In an induced draft system the blower is exposed to hot and potentially corrosive flue gases and, therefore, should be made of materials that can withstand these conditions.

Using a fan to force the flue gases through the baffle with either an induced-draft blower (downstream of the water heater) or a forced-draft blower (upstream of the water heater), can increase the RE and reduce the off-cycle flue losses. The increased RE resulting from this design option may necessitate relining or otherwise modifying some venting systems to prevent corrosion or damage from condensation.

Several manufacturers currently make water heaters with induced-draft blowers. However, this feature is usually added to allow sidewall venting and may not be accompanied by any increase in flue baffling.

Some manufacturers make water heaters with induced draft fans that, in addition to pulling the combustion products through the water heater, also draw excess air into the flue gases prior to venting. The additional air cools the flue gases lowering temperature enough so that standard PVC piping can be used for venting. This eliminates any problems with corrosion. Plastic piping is often cheaper and easier to install than sheet metal or masonry chimneys. While this technique of flue gas dilution does not necessarily increase water heater efficiency by itself, when combined with an improved flue baffle that increases RE, it can help avoid venting problems.

As discussed earlier under venting issues, design options with REs greater than 80% were not considered in this analysis. At REs beyond 80%, flue-loss efficiencies exceed 84% resulting in flue gas condensation within the water heater's flue, leading to corrosion and a shortened life. To ensure that condensation would not occur within the flue system, only flue baffle improvements with maximum REs of 78% were included in design options selected for further analysis. By keeping recovery efficiencies this low, it was assumed that forced- or induced-draft blowers would not be needed to overcome increased pressure drops due to the improved baffle system.

Table 32 summarizes the changes made to the analytic baseline model to simulate the performance of a gas-fired water heater with an improved flue baffle. In order to model a water heater with a 78% RE, the excess combustion air was decreased and the flue baffle heat exchanger multiplier was increased.

Table 32. Gas-Fired Water Heater Modeling Differences Analytic Baseline Model vs. Model with Improved Flue Baffle

Descriptive parameter	Analytic Baseline	w/ Improved Flue Baffle (RE = 78%)
Excess Combustion Air (%)	42.0	34.0
Flue baffle effectiveness multiplier	2.000	2.200

Electronic Ignition. The most commonly used ignition system in gas-fired storage water heaters is a standing pilot ignition system. The disadvantage of a standing pilot is it burns gas continuously at a rate of approximately 400 Btu/h (117 W), and only part of this heat is converted to useful energy. In addition to the standing pilot, three electronic ignition devices are commonly used in gas-fired appliancies:

- an intermittent pilot ignition device that by generating a spark lights a pilot, which in turn lights the main burner
- an intermittent direct ignition device that lights the main burner directly by generating a spark, and
- a hot surface ignition (HSI) device that lights the main burner directly by generating a hot surface.

Unlike standing pilots that consume gas continuously, these devices operate only at the beginning of each on-cycle. Although there is no increase in the steady-state efficiency with use of electronic ignition devices, the overall fuel consumption may be reduced. Burner on-time may increase to make up for the heat the standing pilot would have supplied during standby periods.

Electronic ignition devices require an outside electricity source for ignition, usually a 24 V or a 120 V system. The power draw of the electrically operated gas valve is between 5 W and 12 W, and power is consumed only when there is a call for heat. Electronic ignition systems also require a control module, which houses the electronic control circuitry and consumes 6 W of power during a call for heat. These systems also need an electronic thermostat that draws 1.2 W of power during the heating period and 0.4 W of power during the standby period. The HSI is a resistive device that draws about 2.5 amps at 120 V (about 300 W of power) for approximately 30 seconds during ignition.

For this analysis, an intermittent pilot ignition system was the only type of non-standing pilot ignition system analyzed for gas-fired storage water heaters. The total on-cycle power consumption was assumed to be 15.7 W while the total off-cycle power consumption was assumed to be 0.4 W. Table 33 summarizes the changes made to the analytic baseline model to simulate the performance of an intermittent pilot ignition system.

Table 33. Gas-Fired Water Heater Modeling Differences Analytic Baseline Model vs. Model with Electronic Ignition

Descriptive parameter	Analytic Baseline	with Electronic Ignition
Pilot Input	400 Btu/hr (117 W)	0 Btu/hr (0 W)
On-cycle power consumption	0.0 W	15.7 W
Off-cycle power consumption	0.0 W	0.4 W

Flue Damper (Electromechanical). Gas-fired storage water heaters are equipped with a draft hood connecting the flue to a vent pipe or chimney. During off-cycle, the water heater loses heat by natural convection up the flue. A damper can be installed either at the flue exit or in the vent pipe to minimize the off-cycle heat losses. A flue damper is installed upstream of the draft diverter, while the vent damper is installed downstream of the draft diverter.

Electric flue dampers are activated by an external source of electricity. The dampers open before combustion starts and close immediately after combustion stops. When the damper reaches the open position, an interlock switch energizes the solenoid and enables the gas ignition circuit. Therefore, the burner cannot be ignited when the damper is in the closed position. Because the dampers open and close immediately, no bypass is needed. For flue dampers installed on water heaters using a standing pilot, a knockout in the flue damper is provided to vent the pilot's flue gases. Of course in this situation, off-cycle losses would be greater than those in water heating equipment using a non-standing pilot ignition system. The electric flue damper needs a 24-volt electric source and consumes about 5 W when the gas supply is off.

Flue dampers are assumed to have no effect on the RE of the water heater.

For this analysis, electromechanical flue dampers were analyzed only in conjunction with electronic ignition systems. Since electricity is required for the operation of the flue damper, it was assumed that the standing pilot would be converted over to an electronic ignition system in order to take advantage of the electrical power that exists at the water heater. Flue dampers were modeled according to the procedure outlined in the user's manual for TANK[39]. Typically, TANK calculates the off-cycle pressure loss coefficient based on the physical characteristics of the water heater. In the case of a flue damper, the off-cycle pressure loss coefficient is manually determined based on the following expression:

$$e_{vd} = \frac{1}{(c \cdot f)^2}$$

where;

e_{vd} = the effective pressure loss coefficient of the flue damper,
c = discharge coefficient of the flue damper, and
f = fraction of center flue area remaining open after the flue damper has closed expressed by the following equation:

$$f = \frac{D_f^2 - D_d^2}{D_f^2}$$

where;

D_f = the internal flue diameter, and
D_d = the electromechanical flue damper diameter.

Because flue dampers are usually not designed to completely seal the flue, the fraction of the center flue remaining open after the damper closes is approximately 10%. Discharge coefficients vary from a value of 0.6 for knife-edged damper plates to 1.0 for smooth-edged damper plates. For purposes of this analysis, a value of 0.8 was assumed for the discharge coefficient while a value of 10% was assumed for the fraction of the center flue remaining open in order to calculate the pressure loss coefficient for a water heater utilizing a flue damper. Table 34 summarizes the changes made to the analytic baseline model to simulate the performance of an electromechanical flue damper.

Table 34. Gas-Fired Water Heater Modeling Differences: Analytic Baseline Model vs. Model with Electromechanical Flue Damper

Descriptive parameter	Analytic Baseline	with Electromechanical Flue Damper
Off-cycle pressure loss coefficient	12.4047	156
Off-cycle power consumption	0.0 W	5.0 W

Side-Arm Heater. The side-arm heater design avoids large flue losses by removing the flue from the center of the tank. Water is withdrawn from the bottom of the tank and heated over a burner in a small, separate heat exchanger. Water is returned to the top of the tank. A small circulation pump moves water through the heat exchanger when the burner is on. The burner could have electronic ignition, which would reduce the pilot light losses. Auxiliary power is supplied by a low-voltage plug-in transformer. A water heater using this design in combination with electronic ignition and a plastic tank was commercially available until 1998.

The expected EF and RE for a gas-fired water heater with a side-arm heater were based on information provided by Mr. Minniear[40]. Table 35 provides EF estimates for two types of 40 gallon (150 liter) gas-fired storage water heater with side-arm heaters and metal storage tanks. One design is based on a 76% RE while the other is based on a 78% RE. Both designs incorporate an intermittent pilot ignition device, 1.981 in. (5.032 cm) of HFC-245fa foam insulation, and plastic heat traps.

Table 35. Side-Arm 40 gallon (150 liter) Gas-Fired Water Heater: Energy Factor Estimates

Water Heater Design	**Energy Factor**
76% RE Side Arm Heater with intermittent pilot ignition device, 1.981 in. (5.032 cm) foam insulation, and plastic heat traps	0.655
78% RE Side Arm Heater with intermittent pilot ignition device, 1.981 in. (5.032 cm) foam insulation, and plastic heat traps	0.668

Because TANK cannot simulate the performance of water heaters equipped with side-arm heaters, the WHAM energy calculation method was used to estimate its energy performance. If both the EF and RE are known, WHAM can be used to determine the UA of the water heater and, in turn, its energy consumption. Appendix B provides a detailed explanation of how the WHAM energy calculation method was used to determine the energy consumption of side-arm heater designs.

Since side-arm heaters require a small circulation pump to move water through the heat exchanger, a component of the total energy input is due to the consumption of electrical energy. For this analysis, it was assumed that the circulation pump had an on-cycle power consumption of 30 W. The daily electrical energy use was determined by modeling the flue damper water heater with the TANK simulation model and specifying an on- and off-cycle power consumption equal to that assumed for a side-arm heater. Since side-arm heaters already need electricity to operate, an intermittent pilot ignition system was also included as part of the side-arm heater. For modeling purposes, the on-cycle power consumption was assumed to be 45.7 W (30 W for the circulation pump and 15.7 W for the intermittent ignition device) while the off-cycle power consumption was assumed to be 0.4 W (for the intermittent ignition device). Using TANK, this results in a daily electrical energy consumption of 80.3 watt-hours.

Plastic Tank. The lower heat conductivity of a plastic tank reduces the amount of heat conducted through the tank wall to the insulation. Plastic tanks cannot be used with standard center-flue gas-fired water heaters because the plastic cannot withstand the high temperatures produced by the flames. This option was considered only with indirect water heating techniques (e.g., the side-arm water heater) that avoid flame temperature problems.

Because indirect water heating techniques cannot be modeled with TANK, the efficiency benefits due to plastic tanks were not estimated with TANK. Plastic tanks were only analyzed in the context of a side-arm heater design. Based on estimates provided by Mr. Minniear, a side-arm heater coupled with a plastic tank insulated with 2 nominal in. of foam insulation, (1.981 in. (5.032 cm)) plastic tank, plastic heat traps, and an intermittent pilot ignition device yields only a slightly higher EF than comparable metal tank designs. Table 36 provides the EF estimates for two 40 gallon (150 liter) gas-fired side-arm storage water heater designs. One is based on a RE of 76% while the other is based on a 78% RE. Both designs utilize a plastic tank, intermittent pilot ignition device, 2 nominal in. (1.981 in. (5.032 cm) of HFC-245fa foam insulation, and plastic heat traps.

Table 36. Side-Arm 40 gallon (150 liter) Gas-Fired Water Heater, Plastic Tank: Energy Factor Estimates

Water Heater Design	**Energy Factor**
76% RE Side Arm Heater with intermittent pilot ignition device, 1.981 in. (5.032 cm) foam insulation, and plastic heat traps	0.662
78% RE Side Arm Heater with intermittent pilot ignition device, 1.981 in. (5.032 cm) foam insulation, and plastic heat traps	0.675

Design Option Manufacturer Costs

As with electric water heaters, manufacturer costs were primarily based upon data provided by GAMA. The side-arm heater and plastic tank were the only design options, which was analyzed using manufacturing cost provided by Mr. Minniear. All manufacturing cost estimates were based upon the production of a 40 gallon (150 liter) gas-fired water heater and were disaggregated into variable (material, labor, overhead, transportation) and fixed (capital, product design) costs. Design option variable and fixed costs were provided as a per unit cost and expressed as an incremental increase over the baseline design.

Existing Baseline Model. GAMA developed existing baseline model cost estimates for a 40 gallon (150 liter) gas-fired storage water heater with 1 in. (2.5 cm) of foamed jacket insulation blown with HCFC-141b. These baseline model costs were used for this Engineering Analysis. Table 37 presents the baseline model manufacturer costs. The overhead includes the transportation cost too. Note, no fixed costs were assumed for the baseline model.

Table 37. Gas-Fired Water Heater Existing Baseline Model: Manufacturer Costs

Design	Variable Costs (per unit) Material	Labor	Overhead	Total	Fixed Costs (per unit) Capital	Product Design	Total	Total Mfg Cost
Existing Baseline	$75.02	$12.49	$50.10	$137.61	$0.00	$0.00	$0.00	$137.61

Analytical Baseline Model. In order to convert the baseline manufacturer costs associated with foam insulation blown with HCFC-141b to that blown with HFC-245fa, the amount and cost of materials associated with varying thicknesses of HCFC-141b and HFC-245fa foam insulation were developed. Thus, the material costs associated with a particular level of HFC-245fa insulation could easily be determined by adding to the baseline costs associated with a comparable level of HCFC-141b foam insulation. Tables 38 and 39 summarize the material costs associated with varying levels of HCFC-141b and HFC-245fa foam insulation, respectively. The material costs of HCFC-141b ($1/lb or $2.2/kg) as well as sheet metal cost ($0.30/lb or $0.66/kg), were based on estimates by Mr. Minniear[41]. The material costs of HFC-245fa foam insulation ($1.32/lb or $2.9/kg) were based on estimates by Allied Signal, see Table 15.

Table 38. Gas-Fired Water Heater Material Costs Associated with varying thicknesses of HCFC-141b Foam Insulation

Polyurethane Foam 141b thickness *in. (cm)*	volume[1] *ft^3 (m^3)*	weight[2] *lb (kg)*	cost[3]	Jacket Sheet Metal area *ft^2 (m^2)*	thickness *ft^3 (m^3)*	weight[4] *lb (kg)*	cost[5]	Misc cost[6]	Total cost
0.98 (2.49)	1.57 (0.04)	3.15 (1.43)	$3.15	23.76 (2.21)	0.038 (0.001)	18.40 (8.35)	$5.52	$0.00	$8.66
1.48 (3.76)	2.47 (0.07)	4.93 (2.24)	$4.93	25.43 (2.36)	0.040 (0.001)	19.69 (8.93)	$5.91	$1.62	$12.46
1.98 (5.03)	3.42 (0.10)	6.83 (3.10)	$6.83	27.12 (2.52)	0.043 (0.001)	21.00 (9.53)	$6.30	$4.04	$17.17
2.48 (6.30)	4.43 (0.13)	8.86 (4.02)	$8.86	28.85 (2.68)	0.046 (0.001)	22.34 (10.13)	$6.70	$5.86	$21.43
2.98 (7.57)	5.51 (0.16)	11.02 (5.00)	$11.02	30.62 (2.84)	0.048 (0.001)	23.71 (10.75)	$7.11	$8.59	$26.72

[1] 40 gallon (150 liter) tank dimensions: dia. = 15.8 in (40.1 cm), length = 47.5 in (120.7 cm), combustion chamber height = 6.5 in (16.5 cm)
[2] Foam density = 2 lb/ft^3 (32 kg/m^3)
[3] Foam cost = $1/lb ($2.2/kg)
[4] Sheet metal density = 489 lb/ft^3 (7833 kg/m^3)
[5] Sheet metal cost = $0.30/lb ($0.66/kg)
[6] Miscellaneous cost includes additional cost for foam dams to contain foram insulation in a larger cavity.

Table 39. Gas-Fired Water Heater Material Costs Associated with varying thicknesses of HFC-245fa Foam Insulation

Polyurethane Foam 245fa				Jacket Sheet Metal				Misc	Total
thickness[1]	**volume[2]**	**weight[3]**	**cost[4]**	**area**	**thickness[1]**	**weight[5]**	**cost[6]**	**cost[7]**	**cost**
in. (cm)	*ft^3 (m^3)*	*lb (kg)*		*ft^2 (m^2)*	*ft^3 (m^3)*	*lb (kg)*			
1.00 (2.54)	1.61 (0.05)	3.21 (1.46)	$4.24	23.82 (2.21)	0.038 (0.001)	18.44 (8.36)	$5.53	$0.00	$9.77
1.48 (3.76)	2.47 (0.07)	4.93 (2.24)	$6.51	25.43 (2.36)	0.040 (0.001)	19.69 (8.93)	$5.91	$1.62	$14.03
1.98 (5.03)	3.42 (0.10)	6.83 (3.10)	$9.02	27.12 (2.52)	0.043 (0.001)	21.00 (9.53)	$6.30	$4.04	$19.36
2.48 (6.30)	4.43 (0.13)	8.86 (4.02)	$11.70	28.85 (2.68)	0.046 (0.001)	22.34 (10.13)	$6.70	$5.86	$24.26
2.98 (7.57)	5.51 (0.16)	11.02 (5.00)	$14.55	30.62 (2.84)	0.089 (0.001)	23.71 (10.75)	$7.11	$8.59	$30.25

[1] Thickness increased due to increased conductivity of 245fa relative to 141b.

[2] 40 gallon (150 liter) tank dimensions: dia. = 15.8 in (40.1 cm), length = 47.5 in (120.7 cm), combustion chamber height = 6.5 in (16.5 cm)

[3] Foam density = 2 lb/ft^3 (32 kg/m^3)

[4] Foam cost = $1.32/lb ($2.9/kg)

[5] Sheet metal density = 489 lb/ft^3 (7833 kg/m^3)

[6] Sheet metal cost = $0.30/lb ($0.66/kg)

[7] Miscellaneous cost includes additional cost for foram dams to contain foam insulation in a larger cavity.

As noted in Table 39, the actual thickness level for 1 nominal in. of HFC-245fa foam insulation was assumed to be slightly greater than the thickness for HCFC-141b foam insulation due to HFC-245fa's higher conductivity.

Table 40 presents the manufacturer cost estimates for a 40 gallon (150 liter) gas-fired water heater with 1 nominal in. of HCFC-141b foam insulation and the costs associated with the same baseline model with HFC-245fa foam insulation. The material costs for the HCFC-141b baseline model were adjusted upward by the difference in material costs ($1.11) calculated for the HCFC-141b and HFC-245fa models.

Table 40. Gas-Fired Water Heater Baseline Model with HCFC-141b and HFC-245fa: Manufacturer Costs

	Variable Costs (per unit)				Fixed Costs (per unit)			Total
						Product		Mfg
Design	**Material**	**Labor**	**Overhead**	**Total**	**Capital**	**Design**	**Total**	**Cost**
Baseline w/ 141b - 0.981 in (2.492	$75.02	$12.49	$50.10	$137.61	$0.00	$0.00	$0.00	$137.61
Baseline w/ 245fa - 1.0 in (2.5 cm)	$76.13	$12.49	$50.10	$138.72	$0.00	$0.00	$0.00	$138.72

Analytical Baseline Model with Flammable Vapor Ignition Resistant Design. In order to prevent the ignition of flammable vapors, gas-fired water heater manufacturers will need to redesign their product. Based on discussions with the Water Heater Industry Joint Research and Development Consortium, DOE assumed a placeholder value of $35 was added to the total manufacturing cost ($15 variable costs & $20 fixed cost) for product redesign[42]. The design would not require electricity at the water heater or modifications to the vent system. In addition, DOE assumed that water hater efficiency would not change. Table 39 presents the manufacturer cost estimates for the baseline model with the flammable vapor ignition resistant design.

Table 41. Gas-Fired Water Heater Analytic Baseline Model with Resistant Flammable Vapor Ignition Design: Manufacturer Costs

	Variable Costs (per unit)				**Fixed Costs (per unit)**			**Total**
						Product		**Mfg**
Design	**Material**	**Labor**	**Overhead**	**Total**	**Capital**	**Design**	**Total**	**Cost**
Baseline with 245fa and Flammable Vapor Ignition Resistant Design	$91.13	$12.49	$50.10	$153.72	$20.00	$0.00	$20.00	$173.72

Heat Traps. Manufacturer costs for metal and plastic heat traps were based upon data provided by GAMA. GAMA's data did not provide a separate cost data for metal and plastic heat traps. Data from the heat trap manufacturer Perfection, Inc. was used as a reference. It was assumed that heat trap material cost is based on the following design configurations: Metal heat trap material costs for both the supply and draw lines were based on a ¾-in. (1.9 cm) by 3-in. (7.6 cm) pipe nipple assembly design. Plastic heat trap material costs for the supply line were based on a plastic drop-intube design while those for the draw line were based on a plastic cartridge heat trap design within a combined outlet and and anode rod assembly. Table 42 summarizes the incremental manufacturer costs for incorporating metal and plastic heat traps into a gas-fired water heater. The costs reflect the addition of heat traps to both the supply and draw lines.

Table 42. Heat Traps for Gas-Fired Water Heaters: Incremental Manufacturer Costs

	Incremental Variable Costs (per unit)				**Incremental Fixed Costs (per unit)**			**Total**
						Product		**Incremental**
Design	**Material**	**Labor**	**Overhead**	**Total**	**Capital**	**Design**	**Total**	**Mfg Cost**
Heat Traps (metal)	$2.75	$0.16	$0.21	$3.12	$0.07	$0.13	$0.20	$3.32
Heat Traps (plastic)	$2.75	$0.16	$0.21	$3.12	$0.07	$0.13	$0.20	$3.32

1) Perfection Inc.'s data was almost identical for both types ($3.00 for plastic and $2.95 for metal heat traps); 2) GAMA's heat trap variable costs are different for electric water heaters and gas-fired water heaters.

Increased Jacket Insulation. Since the current insulation blowing agent, HCFC-141b will be phased out by 2003, manufacturer cost estimates for increases in the jacket insulation were adjusted to account for insulation blown with HFC-245fa. Foam cost data were based on information provided by Allied Signal. As presented earlier, Table 39 depicted the material costs for varying levels of HFC-245fa foam insulation. GAMA provided variable and fixed cost data for jacket insulation increases from a baseline level of 1.0 in. (2.54 cm) to a thickness of 2.0 in. (5.1 cm) only. In order to generate variable and fixed cost data for the next level of insulation, from a baseline level of 1.0 in. (2.54 cm) to a thickness of 2.5 in. (6.4 cm), the data provided by

M. Minniear was used to calculate ratios of variable and fixed cost for 2" insulation to 2.5" insulation. GAMA's cost for 2.0 in. (5.1 cm) of insulation was multiplied by those ratios to approximate the variable and fixed costs for 2.5 in. (6.4 cm) of insulation. Table 43 summarizes the incremental manufacturer costs for jacket insulation increases from a baseline level of 1.0 in. (2.54 cm) to a thicknesses of 1.981 in. (5.032 cm) and 2.481 in. (6.302 cm) (as provided in Table 39). As stated earlier, insulation thicknesses were limited to 2½ in. (6.4 cm) due to installation and shipping concerns.

Table 43. Increased Jacket Insulation for Gas-Fired Water Heaters: Incremental Manufacturer Costs

	Incr. Variable Cost (per unit)				**Incr. Fixed Costs (per unit)**			**Total**
						Product		**Incremental**
Design	**Material**	**Labor**	**Overhead**	**Total**	**Capital**	**Design**	**Total**	**Mfg Cost**
Incr. Insulation - 1.981 in (5.032 cm)	$9.59	$0.60	$4.93	$15.12	$0.85	$0.59	$1.44	$16.56
Incr. Insulation - 2.481 in (6.302 cm)	$14.49	$1.20	$9.86	$25.55	$1.28	$1.18	$2.46	$28.01

Improved Flue Baffle. Manufacturer costs for the improved flue baffle design were based on data from GAMA. Table 44 summarizes the incremental manufacturing costs for an improved flue baffle. The costs were based on a design that increased the RE to 78%. It is interesting to note that largest component of the manufacturing cost increase is the product design.

Table 44. Improved Flue Baffle for Gas-Fired Water Heaters: Incremental Manufacturer Costs

	Incr. Variable Cost (per unit)				**Incr. Fixed Costs (per unit)**			**Total**
						Product		**Incremental**
Design	**Material**	**Labor**	**Overhead**	**Total**	**Capital**	**Design**	**Total**	**Mfg Cost**
Improved Flue Baffle	$0.97	$1.29	$1.32	$3.58	$1.17	$1.72	$2.89	$6.47

Electronic Ignition. Manufacturer costs for electronic ignition were based on the replacement of a standing pilot with an intermittent pilot ignition device. The cost of the electronic ignition system was based on data from GAMA. Table 45 summarizes the incremental manufacturing costs for switching from a standing pilot to an intermittent pilot ignition device.

Table 45. Electronic Ignition for Gas-Fired Water Heaters: Incremental Manufacturer Costs

	Incr. Variable Cost (per unit)				**Incr. Fixed Costs (per unit)**			**Total**
						Product		**Incremental**
Design	**Material**	**Labor**	**Overhead**	**Total**	**Capital**	**Design**	**Total**	**Mfg Cost**
Electronic Ignition	$43.78	$3.28	$11.72	$58.78	$2.09	$1.47	$3.56	$62.34

Flue Damper (Electromechanical). Manufacturer costs for including an electromechanical flue damper with a gas-fired water heater were based on data from GAMA. Table 46 summarizes the incremental manufacturing costs of putting a flue damper on a gas-fired water heater. Because electromechanical flue dampers were analyzed only in conjunction with electronic ignition systems, the incremental manufacturer costs associated with both design options are also summarized in Table 46. As stated previously, because electricity is required for the operation of the flue damper, it was assumed that the standing pilot would be converted to an electronic ignition system in order to take advantage of the electrical power at the water heater.

Table 46. Flue Damper w/ Electronic Ignition for Gas-Fired Water Heaters: Incremental Manufacturer Costs

	Incr. Variable Cost (per unit)				**Incr. Fixed Costs (per unit)**			**Total**
						Product		**Incremental**
Design	**Material**	**Labor**	**Overhead**	**Total**	**Capital**	**Design**	**Total**	**Mfg Cost**
Flue Damper	$85.05	$4.12	$15.87	$105.04	$3.45	$2.03	$5.48	$110.52
Flue Damper + Electr.	$128.83	$7.40	$27.59	$163.82	$5.54	$3.50	$9.04	$172.86

Side-Arm Heater and Plastic Tank. Manufacturer costs for the side-arm heater for a gas-fired water heater design were based on data from Mr. Minniear. Table 47 summarizes the costs for four types of side-arm heater designs; 76% and 78 % RE designs that use a metal tank and electronic ignition and 76% and 78% RE designs with a plastic tank and electronic ignition. For this analysis it was assumed that the cost difference between the 76% and 78% RE designs was equal to the cost of the improved flue baffle design. This assumption means that heat exchanger costs for a 78% RE design would be higher than those for a 76% RE design. Because side-arm heaters were analyzed only in conjunction with electronic ignition systems, the incremental manufacturer costs associated with both design options are also summarized in Table 47. As discussed previously, plastic tanks cannot be considered as a stand-alone design option for standard center-flue gas-fired water heaters due to the high temperature of combustion. Thus, plastic tanks can only be considered with indirect heating designs, such as a side-arm heater.

Table 47. Side-Arm Heaters for Gas-Fired Water Heaters: Incremental Manufacturer Costs

	Incr. Variable Cost (per unit)				**Incr. Fixed Costs (per unit)**			**Total**
						Product		**Incremental**
Design	**Material**	**Labor**	**Overhead**	**Total**	**Capital**	**Design**	**Total**	**Mfg Cost**
76% RE Side-Arm Heater w/ Metal Tank	$24.50	$2.10	$7.20	$33.80	$4.00	$10.00	$14.00	$47.80
78% RE Side-Arm Heater w/ Metal Tank	$25.47	$3.39	$8.52	$37.38	$5.17	$12.72	$16.89	$54.27
76% RE Side-Arm Heater w/ Plastic Tank	$29.75	$2.90	$9.25	$41.90	$8.00	$16.00	$24.00	$65.90
78% RE Side-Arm Heater w/ Plastic Tank	$30.72	$4.19	$10.57	$45.48	$9.17	$17.72	$26.89	$72.37
76% RE Side-Arm Heater w/ Metal Tank including IID	$68.28	$5.38	$26.02	$99.68	$6.34	$3.49	$9.83	$109.51

Design	Incr. Variable Cost (per unit) Material	Labor	Overhead	Total	Incr. Fixed Costs (per unit) Capital	Product Design	Total	Total Incremental Mfg Cost
78% RE Side-Arm Heater w/ Metal Tank including IID	$69.25	$6.67	$27.34	$103.2	$7.51	$5.21	$12.72	$115.98
76% RE Side-Arm Heater w/ Plastic Tank including IID	$73.53	$6.18	$30.22	$109.9	$9.34	$4.09	$13.43	$123.36
78% RE Side-Arm Heater w/ Plastic Tank including IID	$74.50	$7.47	$31.54	$113.5	$10.51	$5.81	$16.32	$129.83

Design Option Retail Prices

The retail price is considered to be the cost to the consumer of only the water heating equipment. The retail price for an existing baseline 40 gallon (150 liter) gas-fired storage water heater (with HCFC-141b foam insulation) was determined by contacting various plumbing contractors and large retail chains. Since the price of a water heater depends on the length of the manufacturer's warranty, only water heaters warrantied for 5 years were considered to be baseline models. As with electric water heaters, the 5 year warranty was accepted as the shortest warranty period offered by water heater manufacturers (although 1 year warranties have been offered in special cases) and is typically reserved for those models which are produced in large quantities (i.e., baseline models). A longer warranty period, in addition to raising the price, may also indicate the presence of some design feature which would not normally be found in baseline models. Table 48 provides the list of retail prices which went into developing the retail price of the baseline model. For each price listed, the source for that price is also provided. All information presented in Table 48 are from the LBNL Water Heater Database [43].

As shown in Table 48, the average retail price for a baseline 40 gallon (150 liter) gas-fired storage water heater is $149.94 (without taxes). As presented earlier, the baseline manufacturer cost of a HCFC-141b-based water heater is $137.61. Using the average national value for taxes of 5.20% (developed by A.D.L, 1998), yields a retail price of $157.74. Dividing the retail price ($157.74) by the manufacturer cost ($137.61.) yields a manufacturer cost-to-retail price markup of 1.15 (an exact value of 1.14626 is used as a multiplier).

The baseline manufacturer cost-to-retail price markup was assumed constant for the design options considered for this analysis. Thus, the retail price for any modified design was simply determined by multiplying its manufacturer cost by the derived markup of 1.15.

Table 48. 40-Gallon (150 liter) Gas-Fired Storage Water Heater Retail Prices

Source	Manufacturer	Brand	Model	Retail
Little Rock, AR	American Water Heaters	Amerimore	G51-40T34-3NV	$115.00
Little Rock, AR	American Water Heaters	Amerimore	G51-40S33-3NV	$116.00
Salt Lake City, UT	American Water Heaters	American Water Heaters	G51-40T34-3NV	$118.00
West Allis, WI	American Water Heaters	American Water Heaters	Add in later	$126.00
Chicago, IL	American Water Heaters	More-Flo	G51-40T34-3NV	$126.00
Minneapolis, MN	American Water Heaters	More-Flo	G51-40T34-3NV	$126.00
Nashville, TN	American Water Heaters	American Water Heaters	DVG52-40S38-NV	$127.00
Portland, OR	State Industries	Reliance	5-40-NORT	$128.00
Reno, NV	American Water Heaters	American Water Heaters	G51-40T34-3NV	$128.00
Stockbridge, GA	American Water Heaters	Envirotemp	G51-40T34-3NV	$129.00
Atlanta, GA	American Water Heaters	PROLine	G51-40S33-3NV	$129.00
Atlanta, GA	American Water Heaters	PROLine	G51-40S33-3NV	$129.00
Marieeta, GA	American Water Heaters	Envirotemp	G51-40T34-3NV	$129.00
Las Vegas, NV	State Industries	Reliance	5-40-NORT	$129.00
Sacramento, CA	American Water Heaters	American Water Heaters	G51-40T34-3NV	$129.00
Atlanta, GA	American Water Heaters	PROLine	G51-40S33-3NV	$129.00
Atlanta, GA	American Water Heaters	PROLine	G51-40T34-3NV	$129.00
Chicago, IL	American Water Heaters	More-Flo	PVG52-40T50-3NV	$130.00
Denver, CO	State Industries	Reliance	5-40-NORT	$131.00
Phoenix, AZ	State Industries	Reliance	5-40-NORT	$131.00
St. Louis, MO	American Water Heaters	American Water Heaters	G51-40T34-3NV	$131.00
Oklahoma City, OK	State Industries	Reliance	5-40-NORT	$131.00
New Orleans, LA	American Water Heaters	American Water Heaters	G51-40T34-3NV	$131.00
Dallas, TX	State Industries	Reliance	5-40-NORT	$132.00
Emeryville, CA	American Water Heaters	American Water Heaters	G51-40T34-3NV	$133.00
Falls Church, VA	American Water Heaters	PROLine	G51-40T34-3NV	$134.00
Orange, CA	State Industries	Reliance	5-40-NORT	$134.00
West Allis, WI	American Water Heaters	Craftsman		$134.00
Seattle, WA	State Industries	Reliance	5-40-NORT	$134.00
Nashville, TN	American Water Heaters	American Water Heaters	G51-40T34-3NV	$135.00
Lexington, KY	American Water Heaters	American Water Heaters	G51-40T34-3NV	$135.00
Livermore, CA	Sears/State Industries	Kenmore		$139.99
Bensalem, PA	American Water Heaters	Moreflow	G51-40t34-NV	$144.00
Charlotte, NC	American Water Heaters			$147.00
Charlotte, NC	American Water Heaters	More-Flo	G51-40T34-3NV	$147.00
Richmond, CA	Sears/State Industries	Kenmore	33246	$160.00
Emeryville, CA	American Water Heaters	American Water Heaters	G51-40S33-3NV	$161.00
Parkersburg, WV	A.O. Smith		FSG40	$162.88
Livermore, CA	Sears/State Industries	Kenmore		$164.99
Berkeley, CA	Rheem	Rheem	21V40-7N	$167.00
Indianapolis, IN	State Industries		PRV40	$170.00
Berkeley, CA	Rheem	Rheem	21V40S-2	$177.00
Berkeley, CA	Rheem	Rheem	21VR40-7	$177.00
Bethpage, NY	Rheem		RH21V40	$178.50

Source	Manufacturer	Brand	Model	Retail
Winchester, VA	Rheem	Rheem	21V407	$184.00
Marion, IN	A.O. Smith		FSG40	$187.38
Boston, MA	State Industires	POWERMISER 5	33246	$190.00
Boston, MA	State Industires	POWERMISER 5	33246	$200.00
Orange, CA	State Industries	Reliance	5-40-NBRT	$209.00
Berkeley, CA	Rheem	Rheem	21V40T	$222.00
Boston, MA	State Industires	ANNIV. SERIES 10		$250.00
Boston, MA	State Industires	POWERMISER 5	33246	$260.00
Average Retail Cost				**$149.94**

Installation and Maintenance Costs

The installation cost is the cost to the consumer of installing the water heater and is not considered part of the retail price. The cost of installation covers all labor and material costs associated with the replacement of an existing water heater. Delivery, removal, and permit fees are also included.

For the baseline water heater models, data was collected from the same sources as those used to gather retail prices, to establish the installation cost of a 40 gallon (150 liter) baseline gas-fired storage water heater. Table 49 lists the installation costs. The average installation cost was determined to be $159.52. All information presented in Table 49 are from the LBNL Water Heater Database[44].

Table 49. 40-Gallon (150 liter) Gas-Fired Storage Water Heater Installation Costs

Source	Manufacturer	Brand	Model	Installation
Berkeley, CA	Rheem	Rheem	21V40-7N	$65.00
Berkeley, CA	Rheem	Rheem	21V40S-2	$65.00
Berkeley, CA	Rheem	Rheem	21VR40-7	$65.00
Berkeley, CA	Rheem	Rheem	21V40T	$65.00
Falls Church, VA	American Water Heaters	PROLine	G51-40T34-3NV	$75.00
Anchorage, AK	Bradford White			$90.00
Anchorage, AK	Bradford White			$90.00
Stockbridge, GA	American Water Heaters	Envirotemp	G51-40T34-3NV	$119.00
Salt Lake City, UT	American Water Heaters	American Water Heaters	G51-40T34-3NV	$125.00
Denver, CO	State Industries	Reliance	5-40-NORT	$130.00
Little Rock, AR	American Water Heaters	Amerimore	G51-40S33-3NV	$130.00
Little Rock, AR	American Water Heaters	Amerimore	G51-40T34-3NV	$130.00
Little Rock, AR	American Water Heaters	Amerimore	DVG52-40S38-NV	$130.00
Phoenix, AZ	State Industries	Reliance	5-40-NORT	$136.00
Atlanta, GA	American Water Heaters	PROLine	G51-40S33-3NV	$142.00
Atlanta, GA	American Water Heaters	PROLine	G51-40S33-3NV	$142.00
Nashville, TN	American Water Heaters	American Water Heaters	G51-40T34-3NV	$145.00
Nashville, TN	American Water Heaters	American Water Heaters	DVG52-40S38-NV	$145.00

Source	Manufacturer	Brand	Model	Installation
Marieeta, GA	American Water Heaters	Envirotemp	G51-40T34-3NV	$149.00
Livermore, CA	Sears/State Industries	Kenmore		$153.99
Livermore, CA	Sears/State Industries	Kenmore		$153.99
Reno, NV	American Water Heaters	American Water Heaters	G51-40T34-3NV	$154.00
Dallas, TX	State Industries	Reliance	5-40-NORT	$155.00
Charlotte, NC	American Water Heaters			$155.00
Orange, CA	State Industries	Reliance	5-40-NORT	$159.00
Orange, CA	State Industries	Reliance	5-40-NBRT	$159.00
West Allis, WI	American Standard	American Standard		$159.00
St. Louis, MO	American Water Heaters	American Water Heaters	G51-40T34-3NV	$160.00
Dale City, VA	American Water Heaters	Craftsman		$169.00
Las Vegas, NV	State Industries	Reliance	5-40-NORT	$170.00
Richmond, CA	Sears/State Industries	Kenmore	33246	$174.00
Charlotte, NC	American Water Heaters	More-Flo	G51-40T34-3NV	$175.00
Emeryville, CA	American Water Heaters	American Water Heaters	G51-40T34-3NV	$176.00
Emeryville, CA	American Water Heaters	American Water Heaters	G51-40S33-3NV	$176.00
Oklahoma City, OK	State Industries	Reliance	5-40-NORT	$180.00
Lexington, KY	American Water Heaters	American Water Heaters	G51-40T34-3NV	$200.00
Chicago, IL	American Water Heaters	More-Flo	PVG52-40T50-3NV	$209.00
Chicago, IL	American Water Heaters	More-Flo	G51-40T34-3NV	$209.00
Sacramento, CA	American Water Heaters	American Water Heaters	G51-40T34-3NV	$210.00
Boston, MA	State Industires	ANNIV. SERIES 10		$220.00
Boston, MA	State Industires	POWERMISER 5	33246	$220.00
Boston, MA	State Industires	POWERMISER 5	33246	$220.00
Boston, MA	State Industires	POWERMISER 5	33246	$220.00
Bew Orleans, LA	American Water Heaters	American Water Heaters	G51-40T34-3NV	$225.00
Seattle, WA	State Industries	Reliance	5-40-NORT	$231.00
Atlanta, GA	American Water Heaters	PROLine	G51-40S33-3NV	$234.00
Atlanta, GA	American Water Heaters	PROLine	G51-40T34-3NV	$234.00
Minneapolis, MN	American Water Heaters	More-Flo	G51-40T34-3NV	$258.00
Average Installation Cost				**$159.52**

Four design options were assumed to increase the cost of installing a gas-fired water heater: the improved flue baffle, electronic ignition, the electromechanical flue damper, and the side-arm heater.

For several designs, TANK reported flue efficiency close to 80%. For those designs it was assumed a Type B vent connector is required to ensure that condensation would not occur within the vent system. The additional installation cost associated with this vent connector was based on an analysis by GRI and independently verified by PNNL (see Appendix C). As established by GRI, the cost for replacing a single-wall vent connector with a Type B double-wall vent connector is $85 in 1990 dollars[45] or $105.29 in 1998 dollars[a] (conversions from 1990 dollars to 1998 dollars were adjusted by the consumer price index (CPI) from the Bureau of Labor Statistics[46]). It was determined that 51.3% of households[b] required a Type B vent connector[47]. Thus, the average additional installation cost was determined by multiplying the $105.29 cost by 51.3%. This yields a value of $54.01 in 1998 dollars as the representative average installation cost for the improved flue baffle design, or other design options within RE=78%.

The three remaining design options (electronic ignition, electromechanical flue damper, and side-arm heater) all require electricity to operate. The installation cost was increased in order to include the cost to bring electricity to the gas-fired water heater for these design options. This installation cost estimate was also based on data from GRI[48]. Of the added installation cost, $6.20 in 1990 dollars, or $7.68 in 1998 dollars, is required for labor and wiring of every water heater with any of these three design options. Thirty-two percent of households will also require an electrical outlet at the water heater. GRI estimated this cost at $66.15 in 1990 dollars[49]; this is equivalent to $81.94 in 1998 dollars. Thus, the average cost for installing an outlet was determined by multiplying the $81.94 cost by 32%. This yields an average cost of $26.22 in 1998 dollars for the installation of an outlet. This value plus the wiring and labor cost of $7.68 yields a total representative added installation cost of $33.90 in 1998 dollars for the three design options which require electricity to operate.

The electromechanical flue damper was the only design option that was assumed to increase a gas-fired water heater's maintenance cost. The maintenance cost of the flue damper was based on a prior DOE analysis[50], in which the national average flue damper maintenance cost was estimated as $63.64 in 1990 dollars or $78.84 in 1998 dollars. For this analysis, the flue damper was assumed to fail in the tenth year of operation. Using a 6% discount rate, this yields a present value of $44.02 in 1998 dollars or an annualized maintenance cost over the ten year period of $5.98.

With the exception of the electromechanical flue damper, information gathered to date suggests that there is virtually no maintenance of residential gas-fired water heaters. Side-arm heater designs may incur increased maintenance costs due to fouling of the heat exchanger from

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[a] Values in 1990 dollars are converted to 1998 dollars by multiplying the 1990 value by the ratio of the 1998 and 1990 CPI. The 1990 CPI for all urban consumers is 130.7. The 1998 CPI is based on the average CPI during the first three months of the year (161.9).

[b] The 51.3% value was determined by multiplying the total number of water heater installations with either Type B vertical vents (42%) or masonry chimneys (48%) by the fraction of households requiring a Type B vent connector (75%) and the fraction of households not already utilizing Type B vent connectors (76%). Thus, the total number of household requiring a Type B vent connector is represented by the following equation: (42% + 48%)   75%   76% = 51.3%.

hard water, but data has not been identified or provided to confirm this. It should be noted that manufacturers recommend that water heaters be drained and flushed annually to minimize deposition of sediment, maintain operating efficiency and prolong equipment life.

Cost-Efficiency Data

The results of the design option analysis for 40 gallon (150 liter) gas-fired storage water heaters are presented in Tables 50 and 51. Included in the cost and efficiency tables are disaggregated manufacturer costs, retail prices, installation costs, maintenance costs, energy-efficiency and energy use data, and payback periods. Design options were added to the baseline model in order of shortest payback period. The payback period for each set of design options was calculated relative to the baseline design according to the following relationship:

$$PAYBACK = \frac{\Delta CC}{\Delta OC} = \frac{\Delta RC + \Delta IC}{\Delta EC + \Delta MC}$$

where;
PAYBACK = payback period (years),
ΔCC = change in consumer cost relative to baseline, ($),
ΔOC = change in operating cost relative to baseline, ($/year),
ΔRC = change in retail cost relative to baseline, ($),
ΔIC = change in installation cost relative to baseline, ($),
ΔEC = change in energy cost relative to baseline, and ($/year),
ΔMC = change in annualized maintenance cost relative to baseline, ($/year).

The existing baseline design with HCFC-141b foam insulation is presented in Table 50 to show the manufacturer cost and retail price differences between the baseline designs with HCFC-141b and HFC-245fa. Also presented in Table 50 are the costs for incorporating a design to resist igniting flammable vapors. For purposes of this analysis, the cost effectiveness of all design options were evaluated in reference to the analytic baseline design with HFC-245fa and the flammable vapor ignition resistant design. Energy costs were from national average energy prices for 2003 from the *1998 Annual Energy Outlook*[51].

The costs for all the design option combinations are shown in Table 50 and the efficiency data is shown in Table 51. A design option selection process is presented as a flowchart in Figure 3. The first selected design option combination is “Analytical Baseline” plus “Heat Traps”, which has the shortest payback period - 2.2 years. This combination is called selection 1. Selection 2 and selection 3 are branches from selection 1 and include “2 in. Jacket Insulation” and “2.5 in. Jacket Insulation” design options. Based on the next shortest payback period, selection 4 is chosen. It includes the “Side Arm Heater” design option and is built on selection 3. The last is selection 5 - “Efficient Flue Baffle”, which is based on selection 2. Table 51a contains efficiency data for the selected design combinations. These selected design combinations are used in the Life Cycle Cost Analysis.

Metal heat traps are not included in the cost-efficiency table because plastic heat traps are more cost effective. The highest EFs are obtained with the side-arm heater designs. No designs pay back in less than 2 years. The gas-fired water heater with heat traps, 2½ in. of insulation, electronic ignition and a mechanical flue damper has a .638 EF, energy savings of 3.96 million Btu of natural gas per year and a payback of 18.96 years. The side-arm gas-fired water heater with efficient flue baffle, 2½ in. of insulation and electronic ignition has a .675 EF, energy savings of 6.45 million Btu of natural gas and a payback of 7.05 years.

Figure 4 graphically depicts the relationship between both increased consumer cost and increased operating cost versus EF.

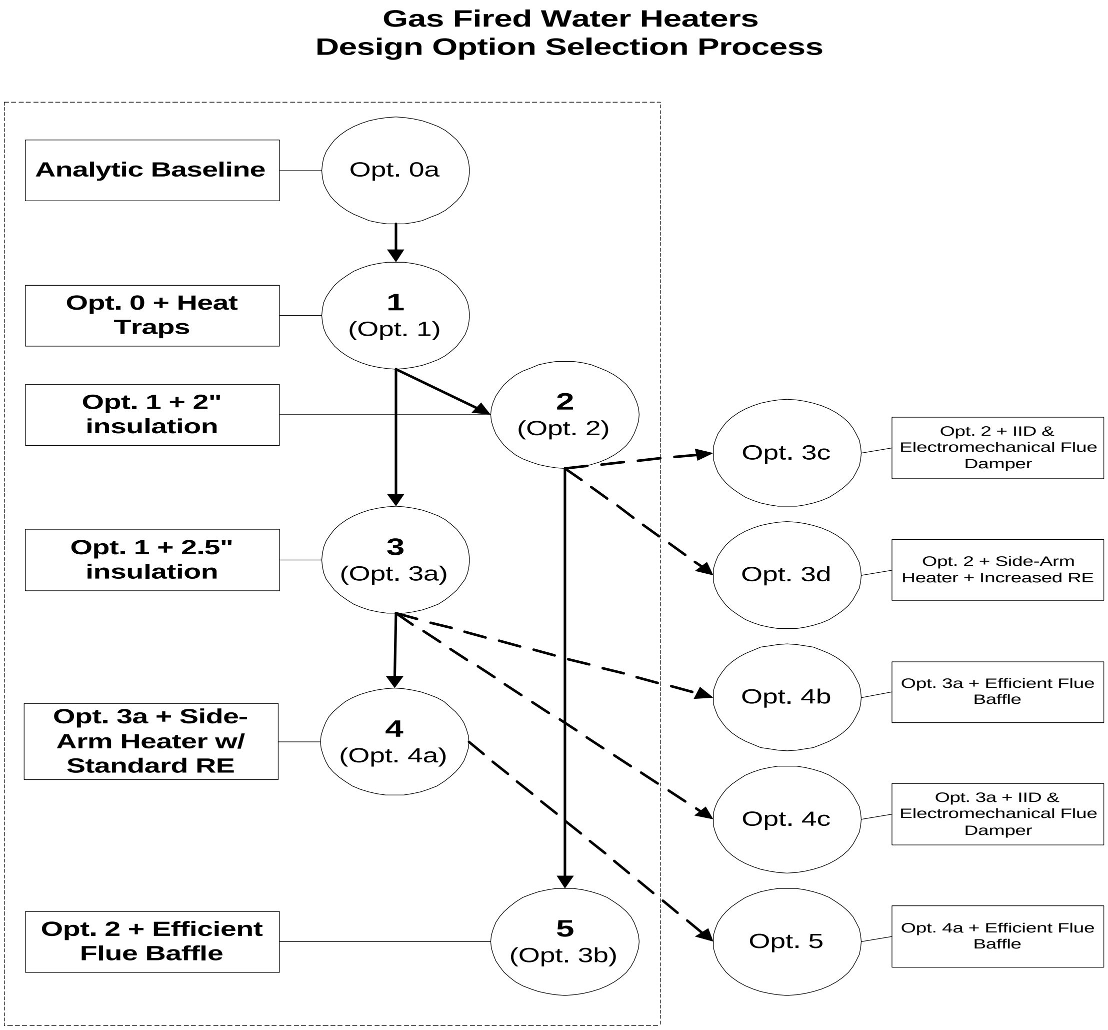

Figure 3. Gas Fired Water Heaters Design Option Selection Process

Table 50. Cost Table for 40 gallon (150 liter) Gas-Fired Storage Water Heater

Design No.	Design Options	Incremental Variable Costs (per unit) [1,2] Material	Labor	Overhead	Total Variable	Incr. Fixed Costs (per unit) [1,2] Capital	Product Design	Total Fixed	Total Mfg Cost	Retail Price[1,4]	Install. Cost[1]	Maint. Cost[1]
0	Existing Baseline [3]	$75.02	$12.49	$50.10	$137.61	$0.00	$0.00	$0.00	$137.61	$157.74	$159.52	$0.00
0a	Analytic Baseline + Resistant Flammable Vapor	$16.11	$0.00	$0.00	$16.11	$20.00	$0.00	$20.00	$173.72	$199.13	$159.52	$0.00
1	0a + Heat Trap	$2.75	$0.16	$0.21	$3.12	$0.07	$0.13	$0.20	$177.04	$202.93	$159.52	$0.00
2	1 + 2" Jacket Insulation	$9.59	$0.60	$4.93	$15.12	$0.85	$0.59	$1.44	$193.60	$221.92	$159.52	$0.00
3a	1 + 2.5" Jacket Insulation	$14.49	$1.20	$9.86	$25.55	$1.28	$1.18	$2.46	$205.05	$235.04	$159.52	$0.00
3b	2 + Improved Flue Baffle	$0.97	$1.29	$1.32	$3.58	$1.17	$1.72	$2.89	$200.07	$229.33	$213.54	$0.00
3c	2 + Electronic Ignition & Flue Damper[5]	$128.83	$7.40	$27.59	$163.82	$5.54	$3.50	$9.04	$366.46	$320.06	$193.42	$5.98
3d	2 + Side-Arm Heater w/ Increased RE[6]	$69.25	$6.67	$27.34	$103.26	$7.51	$5.21	$12.72	$309.58	$354.86	$193.42	$0.00
4a	3a + Side-Arm Heater w/Standard RE[7]	$68.28	$5.38	$26.02	$99.68	$6.34	$3.49	$9.83	$314.56	$360.57	$193.42	$0.00
4b	3a + Improved Flue Baffle[8]	$0.97	$1.29	$1.32	$3.58	$1.17	$1.72	$2.89	$211.52	$242.46	$213.54	$0.00
4c	3a + Electronic Ignition & Flue Damper[9]	$128.83	$7.40	$27.59	$163.82	$5.54	$3.50	$9.04	$377.91	$433.18	$193.42	$5.98
5	4a + Improved Flue Baffle[10]	$0.97	$1.29	$1.32	$3.58	$1.17	$1.72	$2.89	$321.03	$367.98	$247.44	$0.00

[1] All costs and prices in 1998$.

[2] Incremental variable and fixed costs are per unit costs.

[3] For the Existing Baseline Model with HCFC-141b, the TOTAL variable costs are provided.

[4] Retail Prices are calculated based on the manufacturer cost-to-retail price markup of 1.14626 .

[5] Design option 3c: The incremental cost covers Electronic Ignition & Flue Damper.
The total cost includes Heat Trap and 2" Jacket Insulation

[6] Design option 3d: The incremental cost covers 78% RE Side-Arm heater w/ Metal tank and Electronic Ignition (see
The total cost includes Heat Trap and 2" Jacket Insulation

[7] Design option 4a: The incremental cost covers 76% RE Side-Arm heater w/ Metal tank and Electronic Ignition (see
The total cost includes Heat Trap and 2.5" Jacket Insulation

[8] Design option 4b: The incremental cost covers Improved Flue Baffle.
The total cost includes Heat Trap and 2.5" Jacket Insulation

[9] Design option 4c: The incremental cost covers Electronic Ignition & Flue Damper.
The total cost includes Heat Trap and 2.5" Jacket Insulation

[10] Design option 5: The incremental cost covers Improved Flue Baffle.

The total cost includes Heat Trap, 2.5" Jacket Insulation, 78% RE Side-Arm heater w/ Metal tank and Electronic Ignition.

Table 51. Efficiency Table for 40 gallon (150 liter) Gas-Fired Storage Water Heater

Design No.	Design Options	Energy Factor	Recovery Efficiency	UA	Thermal Efficiency[3]	Fuel Energy Use Daily *Btu/day*	Fuel Energy Use Yearly *MMBtu/year*	Electrical Energy Use Daily *kWh/day*	Electrical Energy Use Yearly *kWh/year*	Payback Period [2] *years*
0	Existing Baseline	0.545	75.48%	13.82	77.90%	78289	28.58	0.00	0.00	NA
0a	Analytic Baseline + Resistant Flammable Vapor	0.544	75.56%	13.86	77.90%	78298	28.58	0.00	0.00	NA
1	0a + Heat Trap	0.554	75.57%	12.96	77.90%	77523	28.30	0.00	0.00	2.31
2	1 + 2" Jacket Insulation	0.580	76.21%	11.04	77.85%	75159	27.43	0.00	0.00	3.42
3a	1 + 2.5" Jacket Insulation	0.587	76.38%	10.64	77.74%	74647	27.25	0.00	0.00	4.63
3b	2 + Improved Flue Baffle	0.595	78.01%	10.69	79.75%	72784	26.57	0.00	0.00	7.19
3c	2 + Electronic Ignition & Flue Damper	0.638	76.52%	5.95	77.85%	67465	24.62	0.14	52.77	19.81
3d	2 + Side-Arm Heater w/ Improved Flue Baffle	0.655	76.00%	5.68	-	62483	22.81	0.08	29.32	5.82
4a	3a + Side-Arm Heater	0.662	76.00%	5.24	-	61819	22.56	0.08	29.32	5.97
4b	3a + Improved Flue Baffle	0.600	78.03%	10.37	79.57%	72530	26.47	0.00	0.00	7.19
4c	3a + Electronic Ignition & Flue Damper	0.645	76.71%	5.52	77.84%	66792	24.38	0145	52.77	18.75
5	4a + Improved Flue Baffle	0.675	78.00%	5.36	-	60618	22.13	0.08	29.32	7.28

[1] Annual operating cost for Payback Period calculation established with a gas price of $5.82 /MMBtu and an electricity price of $0.0787 /kWh in 1998$.
[2] Thermal Efficiency is used to determine the risk of venting system corrosion...

Table 51a. Efficiency Table for 40 gallon (150 liter) Gas-Fired Storage Water Heater - Selected Design Option Combinations

Selection No.	Design No.	Design Options	Energy Factor	Recovery Efficiency	UA	Thermal Efficiency[2]	Fuel Energy Use Daily *Btu/day*	Fuel Energy Use Yearly *MMBtu/year*	Electrical Energy Use Daily *kWh/day*	Electrical Energy Use Yearly *kWh/year*	Payback Period[1] *years*
0	0	Existing Baseline	0.545	75.48%	13.82	77.90%	78289	28.58	0.00	0.00	NA
0a	0a	Analytic Baseline + Resistant Flam. Vapor	0.544	75.56%	13.86	77.90%	78298	28.58	0.00	0.00	NA
1	1	0a + Heat Trap (plastic)	0.554	75.57%	12.96	77.90%	77523	28.30	0.00	0.00	2.31
2	2	1 + 2" Jacket Insulation	0.580	76.21%	11.04	77.85%	75159	27.43	0.00	0.00	3.42
3	3a	1 + 2.5" Jacket Insulation	0.587	76.38%	10.64	77.74%	74647	27.25	0.00	0.00	4.63
4	4a	3a + Side-Arm Heater	0.662	76.00%	5.23	-	61819	22.56	0.08	29.32	5.97
5	3b	2 + Improved Flue Baffle	0.595	78.01%	10.69	-	72784	26.57	0.08	0.00	7.19

[4] Annual operating cost for Payback Period calculation established with a gas price of $5.82 /MMBtu and an electricity price of $0.0787 /kWh in 1998$.

[2] Thermal Efficiency is used to determine the risk of venting system corrosion.

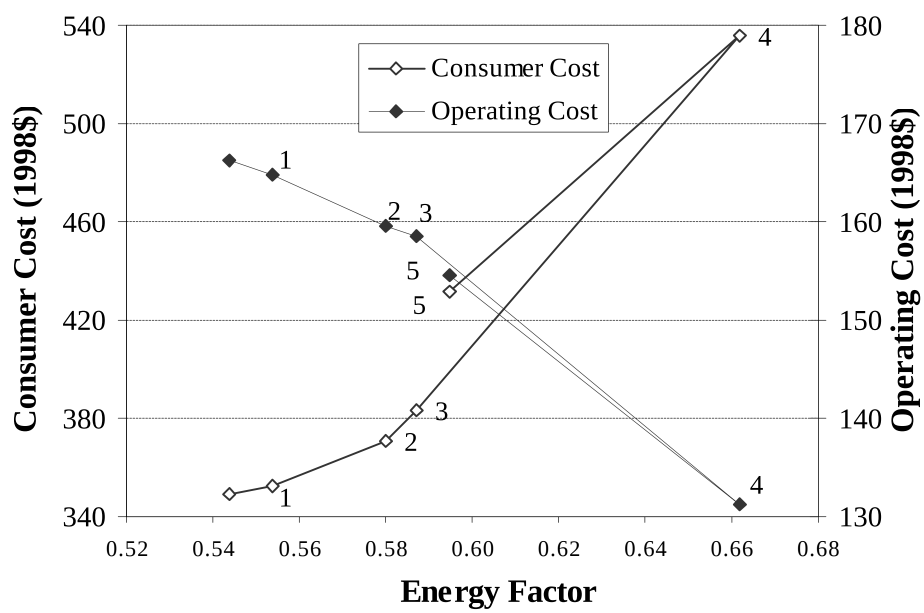

Figure 4. 40 gallon (150 liter) Gas-Fired Storage Water Heaters: Total Consumer Cost and Operating Cost vs. Energy Factor for Selected Design Options Combinations

OIL-FIRED WATER HEATERS

Oil-fired water heaters are typically constructed using a glass-lined metal storage tank located above an insulated combustion chamber. There are two basic design types, center flue and rear flue (also referred to as floating tank design). Both designs utilize an oil-burner consisting of oil pump, blower, ignition device, and controls. The two basic designs are differentiated by flue location. In a center flue design, the combustion products are vented through a center flue that goes up the middle of the storage tank. By contrast, rear-flue designs provide for the combustion gases to travel around the outside of the storage tank. The rear-flue design provides significantly more heat exchange area between the storage tank and flue gases. Thus, these designs typically have higher RE and input ratings compared to center flue designs of similar storage volumes. However, because the hot exhaust gases travel near the outside of the water heater, there is also more heat transfer area for off-cycle losses to the flue. Because center-flue designs are much more common in residential use, the DOE analysis for oil-fired water heaters only considers center-flue designs.

The pump and blower of the water heater are powered by a single motor. The blower provides for proper mixing of oil and combustion air. The oil and air mixture is electrically ignited with a high voltage spark. In most burners, this spark operates continuously as long as the burner is firing. Since the spark does not operate when the burner is off, this is referred to as an intermittent ignition system.

Oil-fired water heaters have higher input ratings than similar sized gas-fired storage water heaters, resulting in higher recovery rates. Because of the relatively high recovery rates, the industry uses storage tank volumes slightly smaller than those used with gas-fired or electric storage water heaters. The oil-fired water heater industry uses two common tank volumes, each with a corresponding input rating. These are either 32 gallon (120 liter) water heaters with an input rating between 85,000 to 95,000 Btu/hr (24,905 to 27,835 watts) or, 50 gallon (189 liter) water heaters with an input rating between 100,000 to 110,000 Btu/hr (29,300 to 32,230 watts). Discussions with installers and manufacturers indicate that the 32 gallon water heater size represents the bulk of the residential market and this is the size used as a baseline model in the engineering analysis.

Existing Baseline Model

The first step in the design options analysis is to characterize the energy usage of the existing model. As stated previously, the existing oil-fired water heater used in this analysis has an EF of 0.529, an RE of 75% and an energy consumption of 90,962 Btu/hr (90,000 Btu/hr of fuel oil and 282 W [962 Btu/hr] for the pump and blower motor) during firing.

Table 52 summarizes the primary baseline characteristics. The jacket insulation was assumed to be 1 in. of HCFC-141b foam, characteristic of water heater models known to closely match DOE's baseline performance criteria. Many existing oil-fired water heater models use fiberglass insulation, however these models typically use more than 1 in. of insulation and have better performance. Note that the analysis did not address the modeling of the combustion chamber and hence no detailed description of the combustion chamber was needed. The values in Table 50 describe the water heater in engineering terms for use in the heat transfer calculations.

Table 52. Oil-Fired Water Heater Baseline Model Characteristics

Descriptive parameter	Value
Input Rating (oil)	90000 Btu/hr (26377 W)
On-cycle power consumption	282 W
Off-cycle power consumption	0.0 W
Tank Dimensions	
Inside Diameter	17.892 in. (40.366 cm)
Steel Wall Thickness	0.054 in. (0.1372 cm)
Height	32.7 in. (83.1 cm)

Volume	32.0 gallons (120 liter)
Jacket Description	
Foam insulation thickness	0.981 in. (2.492 cm)
Sheet metal thickness	0.019 in. (0.0483 cm)
Thermal conductivity of foamed	0.0140 Btu/hr·ft·°F (0.0242
Outer Jacket Emissivity	0.87
Flue Description	
Internal Diameter	6.00 in. (15.24 cm)

In order to determine the daily energy consumption, the first step is to determine the hours of operation. This is done with the following equation.

$$BOH = \frac{Q_{draw}}{EF \cdot P_{on}} \qquad \textbf{(A)}$$

where;

BOH = burner operating hours, the number of hours per day the burner is on (hrs/day),
Q_{draw} = the amount of heat added to the water in the daily draw under the DOE test procedure, (41,094 Btu/day [43,346 kJ/day]),
P_{on} = the total energy consumption rate (both electrical and fuel oil) when the burner is firing (Btu/hr)

For the existing model, this results in 0.854 burner operating hours per day. Using the DOE test procedure as a guideline, the daily energy consumption is calculated from the electrical and oil input rates multiplied by the number of operating hours per day. This results in an oil consumption of 76,860 Btu/day (81,072 kJ/day) and an electrical energy consumption of 241 Wh/day.

The UA from the DOE test procedure was estimated using the following equation:

$$UA = \frac{\frac{1}{EF} - \frac{1}{P_{on}}}{(T_{tank} - T_{amb}) \cdot \left(\frac{24}{Q_{draw}} - \frac{1}{RE \cdot P_{on}} \right)} \qquad \textbf{(B)}$$

Plugging in the appropriate existing model values of EF, RE, and P_{on} results in a UA of 14.494 Btu/hr-°F (7.64 W/°C) for the existing model. By definition, this UA consists of standby heat losses through the tank shell, through fittings, and from the flue during the off-cycle. Table 53 summarizes the results for the energy characteristics of the existing baseline model.

Table 53. Performance Characteristics for Existing Baseline Oil-Fired Water Heater

Description	UA		RE	EF	Oil Use		Electrical Use
	Btu/hr °F	**(W/°C)**			***Btu/day***	***(kJ/day)***	***Wh/day***
Existing Baseline	14.494	(7.64)	75%	0.529	76,860	(81,072)	241

The continuous losses, on-cycle flue losses, and off-cycle flue losses are determined from two equations. The first equation sets two definitions of total daily heat loss equal. It states that the sum of the rates of loss multiplied by the hours of each type of loss equals the total consumption minus delivered energy. The second equation is based on the definition of RE, i.e., the total on-cycle losses equal the energy input minus the hot water energy removed from a tank during the recovery portion of the DOE test procedure. The two equations can be written as follows:

$$24 \cdot Loss\_continuous + (24 - BOH) \cdot Loss\_Flue\_off + BOH \cdot Loss\_flue\_on = Q_{draw} / EF - Q_{draw} \quad \textbf{(C)}$$

$$Loss\_continuous + Loss\_flue\_on = Input \cdot (1 - RE) \quad \textbf{(D)}$$

where;

Loss_continuous	=	continuous losses through the jacket insulation and out the fittings, (Btu/hr) or (Watts),
Loss_flue_on	=	on-cycle losses up the flue, (Btu/hr) or (Watts),
Loss_flue_off	=	off-cycle losses up the flue as well as other off-cycle non-continuous losses, (Btu/hr) or (Watts),

These losses are not used for calculating annual energy consumption, rather they are used as the basis for differences in heat loss rates for other design options.

Analytic Model. Similarly to gas water heaters, the existing model's HCFC-141b foam insulation was replaced with HFC-245fa foam insulation due to the impending phase out of HCFC-141b in 2003. HFC-245fa has a 3.0% higher conductivity than HCFC-141b and for this design option, the conductivity value of the foam insulation in the existing model was increased by 3.0% to a value of 0.0144 Btu/hr-ft-°F (0.0249 W/m •K). To maintain the same R-value of the insulation (and thus maintain constant UA and RE values for the water heater) the thickness of the nominal 1-in. of foam insulation surrounding the tank was increased from 0.981 in. (2.492 cm) actual thickness to 1.01 in. (2.57 cm). This increase in insulation thickness also resulted in an increase of jacket material. Table 54 summarizes the changes that were made to the existing model with HCFC-141b to provide the same performance with HFC-245fa (see Table 53). All further design options assume the use of HFC-245fa for the tank insulation. Table 54 summarizes the results for the energy characteristics of the analytic baseline model.

Table 54. Oil-Fired Water Heater Modeling Differences: Existing Model with HCFC-141b vs. Analytic Model with HFC

Descriptive Parameter	Existing Model	Analytic Model
Jacket Description		
Foam insulation thickness	0.981 *in.* (2.492 *cm*)	1.01 *in.* (2.57 *cm*)
Thermal conductivity of foamed assembly	0.0140 Btu/hr-ft-°*F* (0.0242 W/m-*K*)	0.0144 Btu/hr-ft-°*F* (0.0249 W/m-*K*)

Table 55. Performance Characteristics for Analytic Oil-Fired Water Heater

Description	UA		RE	EF	Oil Use		Electrical Use
	Btu/hr °F	**(W/°C)**			***Btu/day***	***(kJ/day)***	***Wh/day***
Analytic Baseline	14.494	(7.64)	75%	0.529	76,860	(81,072)	241

Heat Traps. Two types of heat traps were analyzed for oil-fired water heaters: metal and plastic. Both types of heat traps prevent the losses associated with the circulation of hot water into the piping distribution system.

An estimate for the reduction of fitting heat losses due to heat traps added to the analytic model was based on the analysis of the same design option applied to gas-fired water heaters. Results from TANK simulations (see analysis of gas-fired water heaters) suggests that metal heat traps reduce the UA of a water heater tank by 0.318 Btu/hr-°F (0.168 W/°C) during the DOE test. The TANK analysis suggested plastic heat traps reduced the UA of the tank by 0.899 Btu/hr-°F (0.474 W/°C). There is no impact on the RE of the analytic model. Subtracting these UA reductions from the UA of the analytic oil-fired model and plugging the new UA into equation (B) without changing the values for the other parameters from the analytic models yields a new estimate for EF. The results of this analysis are shown in Table 56.

Table 56. Analysis Results for Design Option #1 (Heat Traps)

Design Option #1	UA		RE	EF	Oil Use		Electrical Use
	Btu/hr °F	***(W/°C)***			***Btu/day***	***(kJ/day)***	***W-h/day***
Metal Heat Trap	14.176	(7.476)	75%	0.532	76,363	(80,547)	239
Plastic Heat Trap	13.595	(7.17)	75%	0.539	75,456	(79,590)	236

For this analysis, plastic heat traps will be the chosen design option. Manufacturing costs appear to be roughly comparable between metal and plastic traps and plastic heat traps are considerably more effective in reducing the water heater standby losses.

Note, using the results from TANK in this manner is slightly conservative. Since oil-fired water heaters have larger recovery rates, they spend more of the "Standby" portion of the DOE test not firing. Thus, they will have longer periods for which heat traps are useful and consequently heat traps should have slightly higher benefits on oil-fired water heaters compared with gas-fired water heaters. This has not been accounted for in this analysis.

Increased Jacket Insulation. This design option replaces the nominal 1-in. (2.54 cm) of foam insulation surrounding the storage tank in the existing tank design with 2 in. (5.08 cm) of polyurethane foam insulation around the sides and top of the tank. The diameter of the tank increases to 22 in. (56 cm) and the total height of the water heater (including the combustion chamber) increases to 51 (130 cm) in.. It is assumed that there are no changes to the thickness of insulation surrounding the combustion chamber and no benefit has been calculated for this. No other changes to the tank design are assumed in this analysis except to enlarge the entire water heater jacket to accommodate the increased thickness of insulation.

A water heater designer will either increase the fiberglass insulation thickness around the combustion chamber, or increase the internal dimensions of the combustion chamber to maintain a smooth cylindrical jacket on the water heater. These will add additional costs to the design. The addition of insulation may require a way to recess the burner or to increase the length of the burner blast tube to maintain proper placement of the nozzle in the combustion chamber. This analysis does not account for any modifications to the heat loss from the combustion chamber.

Jacket heat losses are calculated as conductive losses through the insulation to the jacket in series with convective and radiative heat transfer from the jacket to the surrounding air and environment. The side insulation is modeled as a hollow cylinder with the inner diameter equal to the tank diameter (18 in. [45.7 cm]) and the same height as the tank (32.7 in. [83.1 cm]). The top insulation is modeled as a disk (18 in. diameter [45.7 cm]) with a hole for the flue in the center (6 in. diameter [15.2 cm])). The details of the calculation of the total conductive heat loss from the top and sides of the storage are provided in Appendix D.

Both RE and UA are changed by this reduction in total jacket heat loss as it occurs continuously during water heater use. Since jacket losses are continuous losses, they are related to the RE through equation (D):

$$Loss\_continuous + Loss\_flue\_on = P_{on} \cdot (1 - RE) \qquad \textbf{(D)}$$

Thus,

$$RE = 1 - (Loss\_continuous + Loss\_flue\_on) / P_{on} \qquad \textbf{(E)}$$

And subtracting the RE for two different levels of jacket loss when all other losses are held constant gives

$$RE_2 - RE_1 = (Loss\_continuous_1 - Loss\_continuous_2) / P_{on} \qquad \textbf{(F)}$$

or

$$RE_2 - RE_1 = (Jacket\_loss_1 - Jacket\_loss_2) / P_{on} \qquad \textbf{(G)}$$

In the DOE test procedure, the UA represents the average rate of tank energy input needed to maintain the tank at a constant temperature during standby. The standby heat loss rate is calculated as:

$$Standby\ heat\ loss\ rate = UA\,(T_{tank} - T_{amb}) \qquad \textbf{(H)}$$

This "standby heat loss rate" is the average rate of heat input needed to maintain a tank at a constant temperature during standby. It includes continuous losses, flue losses when firing, and flue losses and piping losses during the off-cycle. An overall energy balance on the standby period yields:

$$UA\cdot(T_{tank} - T_{amb})\cdot(24 - BOH_{draw}) = (Loss\_continuous + Loss\_flue\_off)\cdot(24 - BOH) + BOH_{st}\cdot P_{on}\cdot(1 - RE) \qquad \textbf{(I)}$$

where;

BOH_{draw} = Burner operating time to make up for hot water drawn from the tank (hr),

BOH_{st} = Burner operating time to make up for standby losses (hr).

BOH_{st} can be calculated from the total energy required during the standby period divided by the energy input during firing. The energy required to make up for losses during the standby period is equal to the energy input for the whole DOE test minus the energy that is actually used to heat water removed from the tank. In equation form, BOH_{st} is:

$$BOH_{st} = 1/ P_{on} \cdot Q_{draw} \cdot (1/EF-1/RE) \qquad \textbf{(J)}$$

And by default

$$BOH_{draw} = BOH-BOH_{st} \qquad \textbf{(K)}$$

Inserting equation (J) in equation (K) and solving for the loss components gives

$$Loss_{continuous} + Loss_{flue\_off} = \frac{UA\cdot(T_{tank} - T_{amb})\cdot(24 - BOH + BOH_{st}) - Q_{draw}\cdot(1 - RE)\cdot\left(\frac{1}{EF} - \frac{1}{RE}\right)}{24 - BOH} \qquad \textbf{(L)}$$

Plugging in the known parameters for the analytic model water heater, and water heater with plastic heat traps gives combined *Loss_continuous* + *Loss_flue_off* values of 742 Btu/hr (217 W), and 695 Btu/hr (204 W) respectively.

With the addition of more insulation, the continuous losses from the plastic heat trap design option are reduced by the difference in the jacket losses between the design with 2 in. (5.1 cm) of insulation (design option 2) and the same design with 1 in. (2.5 cm) of insulation (design option 1 - heat traps). By solving the equations (A), (B), (J) and (L), the UA value and EF value can be found that provides the new combined Loss_continuous +Loss_flue_off value for the water heater with 2 in. (5.1 cm) insulation. Table 57 shows the results of this procedure.

Table 57. Analysis Results for Design Options 2 - 2" Jacket Insulation

Design Option	**Actual Insulation Thickness** ***in. (cm)***	**Calculated Shell Loss,** ***Btu/hr (W)***	**UA,** ***Btu/hr-°F (W/°C)***	**RE**	**EF**	**Oil Use** ***Btu/day (kJ/day)***	**Electrical Use** ***(W-h/day)***
2" Jacket Insulation + Heat Traps	1.981 (4.82)	89.2 (26.1)	12.241 (6.46)	75.1%	0.555	73,285 (77,301)	230

Improved Flue Baffle. As described for gas-fired storage water heaters, improved flue baffle designs allow the extraction of more heat from the exhaust gases and increase the flue-loss (and hence recovery) efficiency of the water heater.

The oil-fired water heater analysis assumes that the improved flue baffle is added after heat traps and 2" jacket insulation. The energy savings for this design option are calculated by assuming that modification of the flue baffle will provide more efficient heat transfer to the storage tank. This design option will allow the water heater to achieve a RE of 0.78 by impacting reduction of *Flue_loss_on* only. No modifications to *Flue_loss_off* or *Loss_continuous* are assumed with this design option.

There do not appear to be significant concerns with condensing flue products at a RE of 0.78. The references regarding the existing rear-flue oil-fired water heaters report REs in this range. Additionally, the premium water heater products sold by Bock Water Heaters all exceed this level of RE[52,53].

Improving the RE alone, from 0.75 to 0.78, while maintaining the sum of *Flue_loss_off* and *Loss_continuous* at 626 Btu/hr (183 W) as in the previous design option (2" jacket insulation) provides an EF of 0.576 as shown in Table 58.

Table 58. Analysis Results for Design Option 3 - Improved Flue Baffle

Design Option	UA *Btu/hr-°F* *(W/°C)*	RE	EF	Oil Use *Btu/day* (*kJ/day)*	Electrical Use *(W-h/day*)
Improved Flue Baffle + 2" Jacket Insulation + Heat Traps	11.786 (6.216)	78%	0.576	70,562 (74,429)	221

Increased Heat Exchanger Surface Area. This is a broad area of design options, generically referred to as Increased Heat Exchange Surface Area. The suggested design option makes use of small projections from the inner flue surface to: 1) increase the heat transfer area and 2) increase turbulence along the inner flue wall. One manufacturer presently builds water heaters that use a flue with many small rectangular fins attached in a helical pattern on the inside flue surface. Variations of this model have the highest efficiency rating listed in the GAMA directory for oil-fired water heaters.

This design option is used here to describe a number of possible design modifications that would increase the surface area for heat exchange between the flue gases and water. These could include increased flue diameter with improved baffling, multiple flues, or internally finned flues. Presently, the only design feature on the U.S. market representative of this design option is the Bock Turboflue system. The Turboflue design uses many small rectangular fins welded in a helical pattern on the inside of the flue. The fins provide increased surface area for heat exchange with the flue gases and they create turbulence in the flue. The use of this type of internally finned flue is assumed to preclude the use of improved flue baffles, and hence the increased heat exchanger surface area design option is really an alternative to the improved flue baffle design option.

The energy performance of the increased heat exchanger surface area design option is modeled by increasing the RE of the 2" jacket insulation (design option 2) to 0.82. Several of the water heater models that include the Turboflue in their design have a listed RE of 0.82. As was done when considering the improved flue baffle design, no modifications to *Flue_loss_off* or *Loss_continuous* are assumed with this design option.

Improving the RE alone, from 0.75 to 0.82 while maintaining the sum of *Flue_loss_off* and *Loss_continuous* at 626 Btu/hr (183 watts) (as in design option 2) provides an energy factor of 0.606. Table 59 shows the resulting performance for Design Option 4 - Increased Heat Exchanger Area.

Table 59. Analysis Results for Design Option 4 - Increased Heat Exchanger Area

Design Option	**UA** ***Btu/hr-°F*** ***(W/°C)***	**RE**	**EF**	**Oil Use** *Btu/day* ***(kJ/day)***	**Electrical Use** ***(W-h/day)***
Increased Heat Exchanger Area + 2" Jacket Insulation + Heat Traps	11.216 (5.915)	82%	0.606	67,149 (70,829)	210

It should be noted that the energy factor estimate arrived at above may be conservative. An examination of the energy performance parameters of several of the water heater models that use the Turboflue design suggested much better energy performance can be achieved. For example, a 32 gallon (121 liter) water heater model 32PP (Bock) utilizes the internally finned Turboflue design and has 1" jacket insulation. However, this model reports an energy factor of 0.66 and an RE of 0.82. Bock's standard design model 32E, also incorporating the Turboflue design, has a reported energy factor of 0.63 and an RE of 0.82.

To illustrate this example, the energy losses for the model 32PP design were partitioned as was done for the analytic model, but using the EF, RE and rated input of the 32PP model. Inserting an EF of 0.66, RE of 0.82, and rated input of 104,000 Btu/hr (30,472 W) from the GAMA directory into equation (B) results in a UA value of 7.652 Btu/hr (4.036 W/°C). Note however, that it should actually be easier to achieve the RE of 0.82 on a water heater when the rated input is the same as the analytic model unit. If the partitioning of losses is done using the EF of 0.66, RE of 0.82, and rated input of 90,962 Btu/hr (26,652 W), the resultant UA is 7.676 Btu/hr-°F (4.052 W/°C). Both of these examples suggest a considerable reduction in UA above what has been assumed for the increased heat exchanger surface area design option. Standby losses for the Bock 32PP model are reduced significantly from that estimated for the increased heat exchanger surface area design option. It is not clear how much of this reduction in standby loss can be attributed to the Turboflue design (possibly by restricting air movement during the off-cycle) and how much is achieved through other means.

Interrupted Ignition. Interrupted ignition devices allow for the ignition spark to be turned off after a flame has been established. Interrupted ignition devices will provide electrical energy savings since the time the spark is operating is shorter than with the intermittent ignition systems in use on present water heater designs. Intermittent ignition systems provide spark continually while the burner is operating. Note, interrupted ignition systems may also increase the life of the spark electrodes somewhat and may reduce maintenance costs.

Interrupted ignition provides electrical energy savings by shutting off the transformer used to make the sparks. A typical intermittent ignition system utilizing an iron-core transformer may draw approximately 1.7 Amps at 110 V during operation[61]. It does this for all burner operation hours, so the daily electrical energy use for the ignition system for the increased heat exchanger surface area design option (the most efficient case of the previous design options) would be calculated as:

$$Intermittent\_Ignition\_Energy = (1.7\ Amps) \cdot (110\ V) \cdot BOH \qquad \textbf{(S)}$$

For the design option 3 - increased heat exchanger surface area, BOH is 0.746 hrs/day from equation (A).

Equation (S) ignores any power factor relationships in the transformer or electronic circuitry. The Intermittent_Ignition_Energy for the increased heat exchanger surface area design option is then calculated to be 140 wh/day.

For an interrupted ignition system, the system fires for approximately 20 seconds each time the burner is ignited. The duration of each water-heater on-cycle is a function of the usage pattern, but the DOE test procedure, with six 10.3-gallon draws per day, will serve as the basis for this analysis. For most water heater designs, there will be a single recovery for each draw, with the length of each recovery period given by 1/6th of BOH_{draw} (see equation Q). For the increased heat exchanger surface area design option water heater, BOH_{draw} equals 0.551 hrs and the recovery period after each draw is thus 0.092 hrs.

Additionally, during the standby period there will be one or more occasions for the burner to fire to make up for standby losses. The working assumption is that the average tank temperature drops 20°F below the set point before firing is initiated, as dictated by the typical water-heater thermostat deadband. The energy required for each recovery is then the product of the actual storage volume of the water heater (estimated at 95% of the rated volume), the density and heat capacity of the water, and the water temperature rise during firing. The time for each individual recovery during standby can then be estimated as

$$BOH_{recovery\_standby} = (\ Vol_{tank} \cdot dens \cdot C_p\ ) \cdot (T_{rise}) / (\ P_{on} \cdot RE) \qquad \textbf{(M)}$$

where;

$BOH_{recovery\_standby}$	=	the average time for **each** recovery during standby (hr)
Vol_{tank}	=	0.95 * rated tank volume (gal)
T_{rise}	=	the difference between the average tank temperature before and after recovery (°F)

Solving the above equation yields an average $BOH_{recovery\_standby}$ equal to 0.0676 hr/day.

The number of draws during standby equals BOHst / BOH $_{recovery\_standby}$. Using design option 3 - increased heat exchanger surface area as a base, this is equal to 2.125 draws during the standby period. Thus, on average, the DOE test procedure would require the burner to fire an average of 8.125 times per day. At 20 seconds of igniter operation per firing, this requires 0.045 hours of ignition operation per day.

The difference between intermittent ignition and interrupted ignition operating time is thus 0.701 hrs per day (0.746 hr - 0.045 hr), saving 131 wh/day of electrical energy. This represents 447 Btu/day reduction in the Loss_burner_on losses. If this energy savings is averaged over the total burner operating hours of 0.749 hrs/day for the increased heat exchanger surface area design option, this represents an average reduction in electrical power draw of 176 W (602 Btu/hr).

Since the P_{on} is reduced by 602 Btu/hr (176 W) and the output of the water heater is unaffected, the definition of RE can be used to construct an equation for the new RE when the design goes to interrupted ignition.

$$RE\_interrupted = (RE\_intermittent \cdot P_{on}\_intermittent) / (P_{on}\_interrupted) \qquad \textbf{(N)}$$

For the water heater described by the increased heat exchanger surface area design option, the change from an intermittant to an interrupted ignition results in an increase in RE from 0.820 to 0.825.

The UA is also affected, since there is some burner operation during the standby period. Again, since the energy input to the tank during the standby period (represented by UA) is changed while the heat energy to the water during standby does not change, the ratio of the UA of the intermittent ignition system to the UA of the interrupted ignition system is equal to the ratio of the input (P_{on}) for the intermittent system to the input of the interrupted ignition system. Hence,

$$UA\_interrupted = UA\_intermittent \cdot (P_{on}\_interrupted / P_{on}\_intermittent) \qquad \textbf{(O)}$$

And solving, UA_interrupted = 11.142 Btu/hr-°F (5.88 **W/°C**). This UA, in combination with a calculated RE of 0.825 results in a EF of 0.610 from equation (B).

The same interrupted ignition analysis can be performed on the improved flue baffle design option. The resulting performance parameters are an RE of 0.785, UA of 11.708 Btu/hr-°F (6.17 **W/°C**), and EF of 0.580. Table 60 shows the resulting performance for Design Option 5 - Interrupted Ignition.

Table 60. Analysis Results for Design Option 5 - Interrupted Ignition

Design Option	**Description**	**UA** ***Btu/hr-°F (W/°C)***	**RE**	**EF**	**Oil Use** *Btu/day* ***(kJ/day)***	**Electrical Use** ***(W-h/day)***
5a	Interrupted Ignition + Improved Flue Baffle	11.708 (6.175)	78.5%	0.580	70,562 (70,829)	83
5b	Interrupted Ignition + Increased Heat Exchanger Area	11.142 (5.876)	82.5%	0.610	67,151 (70,829)	79

NOTE: The savings indicated from the interrupted ignition design option are based on the use of a conventional magnetic transformer to provide high voltages in the ignition system. Electronic high voltage generators used in electronic igniter circuitry typically use about 0.5 Amps, or less than a third the current draw of magnetic igniter circuitry[61],[62]. Assuming the same hours of burner operation as from design option 3 - increased heat exchange, the transition to electronic ignition circuitry from magnetic ignition circuitry in an intermittent ignition system would save 90 Wh/day. This is 70% of the energy saved from going to an interrupted ignition system. However, the adoption of an interrupted ignition system in a water heater with electronic igniter circuitry would result in net energy savings of only 51 Wh/day (176 Btu/day) as compared with intermittent electronic-ignition circuitry. Discussions with oil-fired water heater manufacturers indicates that electronic ignition circuitry is not commonly used in residential water heater burners, but is an available technology.

Design Option Manufacturer Costs

Manufacturing cost estimates for the oil-fired water heater design options are broken down into variable and fixed costs for each design option. These cost estimates are shown in Table 59 and the assumptions and sources behind the estimates are discussed below. Note that all fixed conversion costs have been amortized over a five year period unless otherwise noted, and also amortized over an assumed shipment volume of 5,000 units annually.

Existing Baseline. Baseline cost for the oil-fired water heat tank (without burner) was estimated based on data provided by Mr. Minniear under contract to LBNL[63]. It was recognized that manufacturers of oil-fired water heaters use both fiberglass and foam in their baseline models. For the purposes of this analysis however, the cost for the baseline model, whether foam or fiberglass insulated, are assumed to be equivalent. A calculation of the volume of foam and shell material for the baseline model was made independently of the data supplied by Mr. Minniear. For a 32 gal baseline model the total mass of the insulation was estimated at 2.77 lbs of HCFC141b foam. The unit price for the HCFC141b based insulation was estimated at $1.00/lb, yielding a total cost of the insulation for the 32 gallon water heater of $2.77/unit. Total shell material is 16.87 lbs of steel at $0.30/lb resulting in a manufacturer cost of $5.06. Total material cost for insulation and shell is $7.83. This cost information was used in determining the cost impact of increasing the insulation thickness on oil fired water heaters.

Analytic design option. The analytic model assumed 1.01 in. of HFC245fa based insulation on top and sides of tank. For 32 gal tank, total mass of the insulation was estimated at 2.86 lbs. At $1.32/lb estimated cost for HFC245fa based insulation, total insulation cost was estimated at $3.77. Total shell material was estimated to be 16.93 lbs of steel at $0.30/lb for a total shell cost $5.08. Total material cost for foam and shell is $8.85, an addition of $1.02 for materials over the baseline model. Since the phase out of HCFC141b as a foaming agent is unrelated to the DOE's energy efficiency mandate and will be borne by the manufacturers regardless of mandated efficiency improvements, fixed costs for the analytic design option have not been estimated.

Heat Traps. Variable cost estimates for heat traps are based on data gathered by Mr. Minniear. Variable costs for heat traps were also estimated by a second consultant, Mr. Eugene West. Both estimates were very comparable. Mr. Minniear's estimates are used here as they provided the higher cost (more conservative) estimate and were broken out into variable material, labor, and overhead costs. Fixed conversion costs to incorporate heat traps were developed from product design cost estimates provided by Mr. West[64 65]. For a small manufacturer, capital cost impact to incorporate heat traps was deemed negligible.

2" Jacket Insulation. Variable costs to increase insulation from 1 to 2 nominal in. of (1.01 to 1.981 in. actual thickness) of HFC-245fa based insulation were estimated based on a nominal 1 in. increase in foam on both the top and side walls of the tank. Total foam mass for 2 in. of insulation was estimated at 6.01 lbs. At $1.32/lb for an HFC-245fa based foam, the total foam cost is estimated at $7.93. The corresponding increase in tank jacket size increased the total mass of jacket steel to 19.16 lbs. Assuming an estimated $0.30/lb for jacket metal provided a jacket cost estimated at $5.75. Total material cost for foam and shell is $13.68. An additional cost of $0.76 for miscellaneous costs such as foam stop blocks and larger shipping cartons was incorporated into the material costs based on data provided by Mr. West[65]. Additional labor cost of $0.29/unit and additional overhead burdens of 0.99/unit, provided by the same source, were also incorporated into the variable cost. Finally, the addition of insulation can affect the shipping cost for the water heaters. No data for the increased shipping cost for an oil-fired water heater was provided to LBNL or PNNL; however, an estimate for this impact on shipping cost was made based on GAMA's estimated increase in shipping costs of $2.56 for an increase of 1 in of insulation on gas-fired water heaters[66]. This value was added to the variable cost overhead, resulting in a net cost increase to $9.43 in variable cost over that calculated for the analytic model.

Fixed conversion costs for this design option were based on data provided by Mr. West[67], who estimated that a small manufacturer, using spin forming to shape the top and bottom pans for the water heater, would incur an estimated $18,000 in engineering costs for this design option, and a further $20,000 in capital expenses to modify the production line[65]. It is noted here that a manufacturer who used a die stamping method to produce the top and bottom pans could expect approximately $100,000 in new die costs alone. However, it was believed that for a large manufacturer, cost for dies to cut and form the top and bottom pans would likely have most of that cost amortized over an existing, similar diameter, gas product line.

In addition to the above costs, discussions with manufacturers and installers of oil-fired water heaters have indicated that at least one-half of all installations of oil-fired water heaters are retrofits of a new water heater to an existing oil burner. The oil burner life is typically at least twice that of the typical water heater tank, however in some cases if a new model or brand of water-heater is installed it may be impossible or costly to fit to an existing burner and a complete installation of tank and new burner will be undertaken.

Since the cost of a new burner is a significant fraction of the cost of the water heater tank on most models, it is desirable to be able to attach an existing burner onto a new water heater. This is a significant problem since the extra insulation thickness would affect the burner placement and hence the combustion characteristics of the water heater. The solution, suggested by several industry members; was for the manufacturer to provide a kit that allowed replacement of the nozzle and blast tube on the existing burner with a nozzle and blast tube that was suitable for a new, heavily insulated, model. The estimated cost for manufacturing and stocking this kit was between $20 and $40 based on input from Mr. West[68]. The midpoint of that range, plus a labor charge of $6.50 (20 minutes of service at $19.50/hour) is used as an additional cost when tanks utilizing this design option are retrofit to existing burners.

Improved Flue Baffles. Variable costs for improved flue baffles were estimated as $3.75 for material, $0.55 for labor, and $1.00 per unit for overhead costs based on estimates provided by Max Minniear. Fixed costs for improving the flue baffle design are estimated at $300,000 for production improvements and $500,000 for product design cost based on estimates provided by Mr. Minniear.

Increased Heat Exchanger Surface. Variable costs for providing increased heat exchanger surface area were estimated at $17.25/unit for material costs, $1.75/unit for labor costs and $4.25/unit in overhead. Fixed conversion costs for this design option were estimated at $1,500,000 for production improvements and $500,000 for product design costs. The fixed cost estimates are based on Bock’s Turboflue model.

Interrupted Ignition. Variable costs to incorporate interrupted ignition circuitry in oil burners was estimated at $16.50 material costs based on data provided by Mr. Minniear. Discussions with a burner manufacturer[69] indicated that the burner manufacturers cost differential for interrupted versus intermittent controls was presently between $10 and $15 and that typically these controls are installed on the burner by the burner manufacturer. The burner units with controls are then sent to the water heater manufacturer who subsequently ships the burner to the distributer or equipment dealer. There were not anticipated to be any additional overhead or labor costs for interrupted ignition controls over intermittent ignition controls. It was also the opinion of the person consulted that in the near future, interrupted controls would likely be the primary control option offered on all burners. However, no attempt was made to indicate the effect of this on the interrupted ignition control cost.

No fixed capital costs are anticipated for interrupted ignition. Design costs for the water heater manufacturer are predominantly related to testing and certification of the water heater. These costs are estimated at $25,000 based on similar product testing costs for increased insulation and heat traps submitted by Mr. West. It is assumed that these costs are amortized over a 5 year period.

DOE hopes that GAMA will gather cost data for these design options from GAMA members who produce oil-fired water heaters. If GAMA supply manufacturer cost data, DOE will revise the analysis with the GAMA data and use the consultants data as an independent check on the GAMA data. As of this writing, GAMA has been unsuccessful in gathering this cost data for oil-fired water heaters.

The cost for all the considered design option combinations are shown in Table 61 and the cost for the selected design options is presented in Table 61a. The first selected design option combination is “Analytical Baseline” plus “Heat Traps”, which has the shortest payback period - 3.8 years. This combination is called design option 1. Selection 2 “2 in. of Jacket Insulation” is based on design option 1. Based on the next shortest payback period, design option 3 is chosen. It includes “Improved Flue Baffle” design option and is built on selection 2. The last is selection 5 - “Interrupted Ignition”, which is also based on design option 3. Table 62 and Table 62a presents accordingly the relative first cost, performance and annual energy use predicted for the considered design options and for the selected design options used in this analysis. Those selected design combinations are further used in the Life Cycle Cost Analysis.

Table 61. Cost Table for 32 gallon Oil-Fired Storage Water Heater Design Options

Design No.	Design Options	Incremental Variable Costs (per unit) [1,2] Material	Labor	Overhead	Total Variable	Incr. Fixed Costs (per unit) [1,2] Capital	Product Design	Total Fixed	Total Mfg Cost	Mfg to Retail Markup	Retail Price[1]	Install. Cost[1]	Maint. Cost[1]
0	Baseline (HCFC141b) - 1" foam [3]	$85.00	$18.25	$36.00	$139.25	$0.00	$0.00	$0.00	$139.25	3.20	$445.60	$491.00	$97.14
0a	Analytic (HFC245fa)- 1" foam	$1.02	$0.00	$0.00	$0.00	$0.00	$0.00	$10.00	$140.27	3.20	$448.86	$491.00	$97.14
1	0a + Heat Trap (plastic)	$2.95	$0.05	$0.15	$3.15	$0.00	$1.52	$1.52	$144.94	3.20	$463.81	$491.00	$97.14
2	1 + Increased Insulation to 1.981" (5.032 cm)[4]	$5.59	$0.29	$3.55	$9.43	$0.80	$0.72	$1.52	$155.89	3.20	$498.85	$509.25 [4]	$97.14
3	2 + Improved Flue Baffle (78% RE)[4]	$3.75	$0.55	$1.00	$5.30	$12.00	$20.00	$32.00	$193.19	3.20	$618.21	$509.25 [4]	$97.14
4	2 + Increased Heat Exchanger Surface[4]	$17.25	$1.75	$4.25	$23.25	$60.00	$20.00	$80.00	$259.14	3.20	$829.25	$509.25 [4]	$97.14
5a	3 +Interrupted Ignition[4]	$16.50	$0.00	$0.00	$16.50	$0.00	$1.00	$1.00	$210.69	3.20	$674.21	$509.25 [4]	$97.14
5b	4 +Interrupted Ignition[4]	$16.50	$0.00	$0.00	$16.50	$0.00	$1.00	$1.00	$276.64	3.20	$885.25	$509.25 [4]	$97.14

[1] All costs and prices in 1998$.
[2] Incremental variable and fixed costs are per unit costs.
[3] For the Baseline Model with HCFC-141b, the TOTAL variable costs are provided.
[4] Includes additional installation cost for burner conversion kit for 50% of existing market

Consumer Cost, Installation, and Maintenance Costs for oil fired water heaters.

Sales and installation of residential oil-fired water heaters are typically done by a local residential heating oil dealer. Hence, in most cases, the purchase and installation of the water heater is as a package, making it somewhat difficult to break out installation cost from purchase price. A phone survey of 29 companies dealing in oil-fired water heating equipment was made, with 13 companies providing some form of consumer price data to PNNL. Based on that survey as well as discussion with water heater and burner manufacturers and two oil-heating associations, the following costs were established.

Typical consumer cost for a base performance oil-fired water heater without burner:	**$446**
Typical consumer cost for an oil burner for an oil-fired water heater:	**$285**
Typical installation cost for new oil-fired water heater	**$300-$700**

The estimated installation cost for a typical oil-fired water heater was estimated at $491 based on data provided by seven dealers in the northeastern U.S.[70]. In addition, it was established that at least 50% of oil-fired water heater installations involve fitting a new water heater tank to an existing burner. For the purpose of this analysis, it is assumed that 50% of all oil-fired water heaters sold are for retrofit to an existing burner. Therefore, 50% of the installations of water heaters with 2" of insulation would require an oil burner modification kit. On average, the installation cost would rise to $509.25.

A typical manufacturer to consumer markup of 320% was used across all design options based on the $446 figure for the existing baseline oil-fired water heater cost (without burner), and the estimated manufacturing cost of $139.25 is shown on Table 59.

A typical maintenance contract cost of $97.14/yr was included in Table 59. It is based on data provided by a phone survey discussed previously. This charge is highly variable, depending on the presence of other oil-fired equipment in the residence. Since none of the design options is anticipated to impact maintenance significantly, this charge has no bearing on the final engineering analysis of the design options. It may however impact the final economic analysis when evaluating possible fuel switching.

Relative Cost vs. Efficiency for Oil-fired Water Heater Design Options

Table 62 presents the relative first cost, performance and annual energy use predicted for the design options considered in this analysis. Table 62a presents the relative first cost, performance and annual energy use predicted for the design options selected from this analysis. It also shows the annual energy cost and estimated simple payback for each design option. Annual energy costs were based on residential energy rates of $7.522/MMBtu of oil and $0.0787/kWh of electricity. Design options were selected based on the payback and the energy factor. Those design options well beyond the average life of an oil-fired water heater were not selected.

Table 62. Energy Impact and Simple Payback of Oil-Fired Water Heater Design Options

Design No.	Design Options	Factory Cost	Retail Price	Install. Cost	Energy Factor	Recover Efficienc (%)	UA *Btu/hr-*	**Fuel Energy Use** Daily *Btu/day*	Yearly *MMBtu/*	**Electrical Energy** Daily *Wh/day*	Yearly *kWh/yr*	Annual Energy Cost[1]	Simple Payback
0	Existing	$139.25	$445.60	$491.00	0.529	0.750	14.494	76860	28.05	241	87.9	$217.94	---
0a	Analytic model w/HFC-245fa	$140.27	$448.86	$491.00	0.529	0.750	14.494	76860	28.05	241	87.9	$217.94	---
1	0a + Heat Traps	$144.94	$463.81	$491.00	0.539	0.750	13.595	75456	27.54	236	86.3	$213.96	3.8
2	1 + 2 in. foam insulation	$155.89	$498.85	$509.25	0.555	0.751	12.241	73285	26.75	230	83.8	$207.80	8.7
3	2 + Improved Flue Baffles	$193.19	$618.21	$509.25	0.576	0.780	11.786	70562	25.76	221	80.7	$200.08	13.1
4	2 + Increased Heat Exchanger	$259.14	$829.25	$509.25	0.606	0.820	11.216	67149	24.51	210	76.8	$190.40	17.9
5a	3 + Interrupted Ignition	$210.69	$674.21	$509.25	0.580	0.785	11.708	70562	25.76	83	30.3	$196.11	14.1
5b	4 + Interrupted Ignition	$276.64	$885.25	$509.25	0.610	0.825	11.142	67151	24.51	79	29.0	$186.64	14.1

[1] Annual energy costs are based on residential energy rates of $7.522/MMBtu of oil and $0.0787/kWh of electricity.

Table 62a. Energy Impact and Simple Payback of Selected Oil-Fired Water Heater Design Options

Design No.	Design Options	Factory Cost	Retail Price	Install. Cost	Energy Factor	Recover Efficienc (%)	UA *Btu/hr-*	**Fuel Energy Use** Daily *Btu/day*	Yearly *MMBtu/*	**Electrical Energy** Daily *Wh/day*	Yearly *kWh/yr*	Annual Energy Cost[1]	Simple Payback
0	Existing	$139.25	$445.60	$491.00	0.529	0.750	14.494	76860	28.05	241	87.9	$217.94	---
0a	Analytic model w/HFC-245fa	$140.27	$448.86	$491.00	0.529	0.750	14.494	76860	28.05	241	87.9	$217.94	---
1	0a + Heat Traps	$144.94	$463.81	$491.00	0.539	0.750	13.595	75456	27.54	236	86.3	$213.96	3.8
2	1 + 2 in. foam insulation	$155.89	$498.85	$509.25	0.555	0.751	12.241	73285	26.75	230	83.8	$207.80	8.7
3	2 + Improved Flue Baffles	$193.19	$618.21	$509.25	0.576	0.780	11.786	70562	25.76	221	80.7	$200.08	13.1
5a	3 + Interrupted Ignition	$210.69	$674.21	$509.25	0.580	0.785	11.708	70,562	25.76	83	30.3	$196.11	14.1

[1] Annual energy costs are based on residential energy rates of $7.522/MMBtu of oil and $0.0787/kWh of electricity.

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